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Development of GIS techniques for automated topographic and hydrologic analysis

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DEVELOPMENT OF GIS TECHNIQUES FOR AUTOMATED TOPOGRAPHIC AND HYDROLOGIC ANALYSIS

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2004

CERTIFICATION

I, Chris J. Ryan, declare that this thesis, submitted in fulfilment of the requirements for the award of Doctor of Philosophy, in the School of Civil, Mining and Environmental Engineering, University of Wollongong, is wholly my own work unless otherwise referenced or acknowledged. The document has not been submitted for qualifications at any other academic institution.

Chris J. Ryan

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ABSTRACT

This thesis describes a research project which focuses on improving the accuracy, and extending the capabilities of topographic and hydrologic analysis algorithms. These algorithms can be applied within GIS frameworks for parameterisation of hydrologic models. In this research project, several new algorithms were developed to overcome the observed deficiencies in current algorithms for GIS based analysis of raster Digital Elevation Models (DEMs). These algorithms were used to develop a software product CatchmentSIM which has been made freely available to researchers and practitioners.

CatchmentSIM allows for interpolation of a DEM from contour and streamline data, removal of flat and pit cells, catchment delineation, automated catchment break-up, analysis of impervious areas, modelling of urban catchments, and the hydrologic and geomorphologic analysis of subcatchment properties.

Following the application of CatchmentSIM to a DEM, a simple internal macro language can be used to automatically create files in any binary or text file format. This allows coupling with a full range of Australian and international hydrologic models, including RAFTS-XP, WBNM, RORB, URBS, DRAINS and HEC-HMS.

The algorithms developed during this research were verified by comparative analysis against current approaches, as well as verification in two case studies.

CatchmentSIM enables users to build on the increasingly comprehensive information available in today's GIS world, while avoiding the traditional shortcomings of conventional raster GIS techniques, and maintaining tight coupling with existing 'industry standard' modelling approaches.

ACKNOWLEDGEMENTS

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I am especially grateful for the faithful users who persevered with the software in its initial buggy versions, particularly David Tetley, Michael Bardsley, Steve Gorman, Terry Malone, Rob Swan, Bruce Baron, Don Carroll, David Stephens and many others. The software would not be a shadow of its present state without your contributions.

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I dedicate this research to my father who passed away in July 2003. I will never forget your unwavering encouragement.

1 INTRODUCTION

Hydrology has long been a science which is founded on accurate interpretation of spatial data. As an example, hand delineation of catchments by tracing over topographic contour maps in order to derive area parameters for a lumped hydrologic model is simply a form of spatial data interpretation. With the advent of high-powered low-cost computing, it is now possible for spatial topographic data to be stored in Geographic Information Systems (GIS). Hence, replacement of manual map interpretation techniques with automated algorithms applied within GIS is seemingly a natural scientific progression.

However, the human brain is a remarkable instrument and programming a machine to replicate the complicated human decision structures involved in such topographic and hydrologic analysis presents significant challenges. Hence, many different approaches have been developed in an attempt to solve the catchment delineation problem, as well as the many other human processes that must be replaced to fully automate the process of extracting parameters for hydrologic and hydraulic models from GIS data. Notwithstanding, it is a worthwhile cause, since although computers may not have the unique judgement of a human, they don't mind repeating a task once, twice, or a *trillion* times, whereas such repetition may understandably irritate a human. Hence, computers are able to extract some valuable information from spatial data that humans cannot by simple application of brute force.

This research project is focused on parameterisation of lumped hydrologic models by application of topographic and hydrologic analysis algorithms within GIS environments. Lumped hydrologic models require a user to break-up a catchment into a collection of subcatchments that are linked together in a network relationship. These models operate on the principle that the subcatchments delineated by the user are assumed to have relatively homogeneous hydrologic characteristics. Rainfall hyetographs are then applied to all the subcatchments and are routed downstream according to time-lagged internal formula. This results in calculation of hydrographs at each subcatchment outlet. While individual models vary, the principal method of analysis remains the same. Prior to any of these models being run, they must be supplied with significant amounts of information regarding the topographic and hydrologic attributes of the subcatchments and the characteristics of the storm-events.

The major tasks involved with setting up a lumped hydrologic model are delineation of subcatchment boundaries, calculation of generalised subcatchment parameters and assignment of lag parameters. Presently, these tasks are predominantly completed by hand with reference to topographic maps. Aside from being inherently time-consuming, these manual approaches incorporate a user-subjectivity into the procedures and reduce the reproducibility of the analysis. Thus, the potential of GIS based algorithms to offer speed, accuracy and reproducibility is attractive.

An additional problem encountered when applying lumped hydrologic models is the necessity to quantify parameters that can not be simply measured in the field, or from a map. These include parameters such as lag coefficients and rainfall loss rates. However, while these parameters are not measurable from topographic data, our understanding of hydrology dictates that they must be somehow related to other parameters that are measurable from topographic data, such as slope, area, soil porosity and many others. These relationships are illusive and are likely to themselves vary across time and space. Automation of hydrologic and topographic analysis using algorithms within GIS offers the best potential for these relationships to be quantified. If this can be achieved, it will allow for more accurate assignment of lag parameters within lumped hydrologic models and hence, better models.

This research project incorporates a comprehensive literature review of the current state of progress in the field of integration of hydrologic and hydraulic modelling with GIS systems, and their data structures. This review is documented in Chapter 2 and focuses on the perspectives of theoretical accuracy of algorithm design as well as the speed and usability of their application in software products. The project will then focus on design and development of a new software product aimed to overcome the disadvantages of current approaches as presented in Chapter 3. A new software product was then developed from scratch to incorporate the algorithms and data structures designed in Chapter 3. A comprehensive documentation of the algorithms and associated functionality of the software is provided in Chapter 4.

Although this project is predominantly focused on algorithm design and computational implementation, such work can not be adequately presented without demonstrating the software's resultant capabilities, and verifying the success of the algorithms at meeting their respective design objectives. This is described in Chapter 5, which presents comparative analysis of several new algorithms against current approaches, and also demonstrates the advantages of the hydrologic and geomorphologic analysis tools that have been incorporated into the software. Furthermore, Chapter 6 presents two case studies that demonstrate the capabilities and improvements to existing techniques offered by the new software. Finally, Chapter 7 draws conclusions from the research project and suggests some foundations for future work in the field.

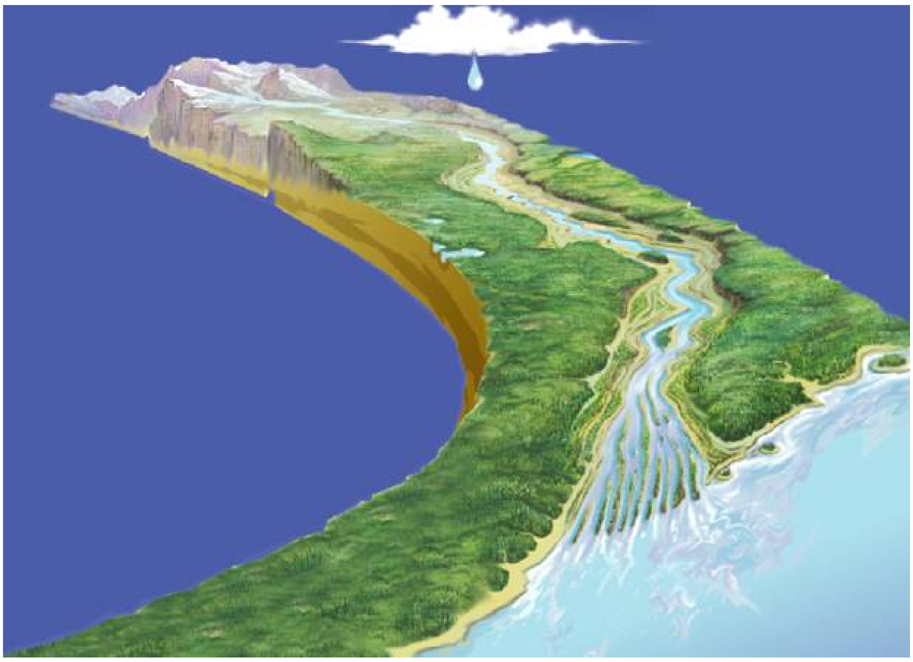
2 LITERATURE REVIEW

2.1 INTRODUCTION

This literature review is intended to explore the potential contribution of GIS aided spatial analysis techniques to hydrologic modelling applications. It presents a brief description of the historical evolution, and more recently co-evolution of these sciences as well as a comprehensive documentation of the '*state of play*' in the field. By necessity, the scope of this literature review is wide reaching in comparison to other research works because automated hydrologic analysis using GIS draws on algorithms and theories from a wide range of research fields; from the theoretical aspects of space and time conceptualisation to the technical intricacies of computational science and merging of software technologies that have developed relatively independently. Due to the scope of the research, this review cannot be as in-depth in all areas as may be desired and the reader may refer to referenced documentation for more information.

2.2 INTERACTION OF GIS AND HYDROLOGIC MODELLING

A Geographic Information System (GIS) is a system of computer software and associated staff organised to maintain and manipulate information that has a specific spatial context. In practice, GIS is a database orientated technology which allows both visual and non-visual data to be stored, managed and interrogated in a relational sense. A fundamental function of GIS systems is the ability to create relationships between data of different types and from within the visual and non-visual domains. These relationships allow GIS to store information about the entire hydrologic cycle and link it together. For example, a catchment (*polygon*) can be linked to its streams (*polylines*) which can be linked to its gauging stations (*points*) and so on. This connectivity offers significant potential to aid in hydrologic modelling due to the various data types that are inherent in the hydrologic cycle. The potential exists for researchers to start modelling water by consideration of discrete quantum or individual drops and to model their progression from where they hit the land surface to their ultimate flow into the ocean as illustrated in **Figure 2-1**.



Source : John M. Evans, USGS as cited in Maidment 2002

Figure 2-1 : A Raindrop Path

The study of hydrology is largely concerned with the application of hydrologic theory to spatial information. Hydrologic models usually use representations of spatial information as generalised parameters. Hence the ability to store, manage and integrate spatial information in GIS provides functionality for hydrologic modelling that model users did not before have access to. Algorithms can be designed to use the GIS data models and determine the parameters required by hydrologic models in a more quick, systematic and reproducible manner. The models may also be coupled with the GIS to ensure the seamless transitioning of this data into the hydrologic modelling software.

In order to analyse the many algorithms that may be applied to GIS data in a hydrologic study it is necessary to first outline the core data types used by GIS systems. These will be described in the following sections.

2.3 GIS DATA MODELS RELEVANT TO HYDROLOGIC MODELLING

2.3.1 Fundamental GIS Data Types

Data types used in GIS can be broadly categorised into two groups, *vector* and *raster* data. Vector data can be broken up into three main groups, points, lines and polygon features of which all are composed of point and/or linear segments. Raster data is composed of rectangular grid cells (*usually square*) of equal size that can represent vector data by particular arrangements of the grid cells. This relationship is illustrated in **Figure 2-2**.

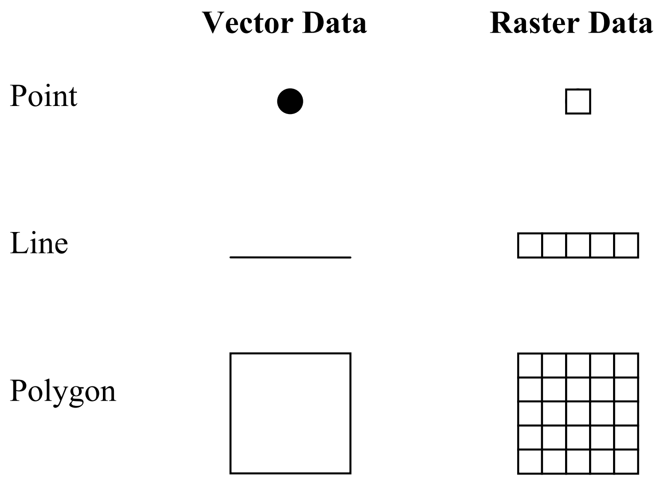


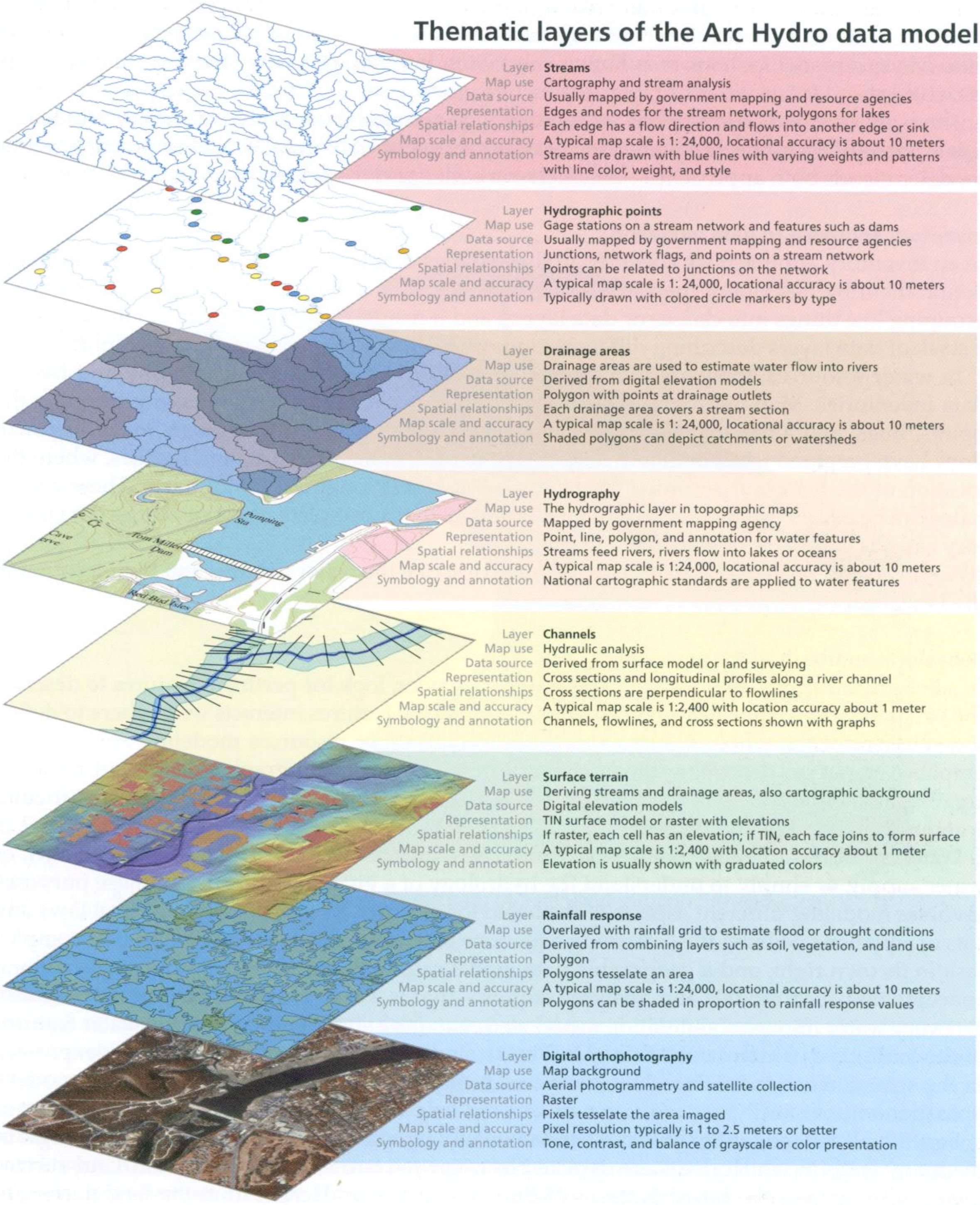
Figure 2-2 : Vector and Raster Data Types

Both vector and raster data are useful spatial data types for GIS analysis and one may be the preferred data type for different types of data. Furthermore, either vector or raster data types may be preferred for the same data set as a function of its intended application. Hence, it is necessary to be able to convert between these data types. Fortunately, algorithms do exist to convert between vector and raster data, however accuracy will be lost during the process. For example, vector data converted to raster format and then back to vector format will not be identical to the original data.

Storage of data in vector format is more precise than raster data formats since points, lines and polygons may have their coordinates located anywhere in space whereas raster data boundary coordinates must be an increment of the cell size of the grid. Vector data storage is also more storage space economical since storage of raster information generally requires storage of information for each grid cell in the raster data space.

However, raster data structures have the advantage of a simple data format which is spatially efficient. For example, a grid cell located in a particular position can be easily located by a quick calculation of the raster boundary co-ordinates and the number of rows and columns in the grid whereas to find a vector attribute in a particular space requires searching through all the vector attributes or advanced spatial indexing systems.

Both vector and raster data representations are needed to accurately represent hydrologic processes in GIS. For example, the Arc Hydro data model employed by ArcGIS (Environmental Systems Research Institute) and descriptions of the associated data types are shown in **Figure 2-3**. It can be seen in this figure that all the previously described data types are used in one or more of the Arc Hydro data model layers.



Source : Maidment 2002

Figure 2-3 : Arc Hydro Data Model

2.3.2 Digital Elevation Models (DEM)

A Digital Elevation Model (DEM) is a derivative of either vector or raster data type that represents the spatial variability of a surface, most commonly land surface elevation. Similarly to the aforementioned GIS data types, DEMs can be developed in raster or vector format. Raster DEMs are a grid structure where each grid cell may have a unique elevation value whereas vector DEMs are usually a Triangular Irregular Network (TIN) which consists of a set of points with x, y, z coordinates connected by triangular planes. Raster DEMs and TINs are very different types of DEMs and perform best in different GIS operations. The advantages, disadvantages and general attributes of these data types will be discussed in the following sections.

Raster DEMs

The most common type of DEM is a raster DEM where each grid cell in a square grid is given an elevation attribute. For example, a raster DEM with 1000 rows and 1000 columns will have 1,000,000 grid cells, each with the capability to hold a unique elevation value. These elevations are stored as an array in a computational sense and are usually stored on disk in a typed binary file to enable quicker processing and reduced hard disk space requirements. An example of a raster DEM is shown in **Figure 2-4** (*on the left side the colours depict the changing elevation where as the right side of the figure shows a 3D depiction of the landscape).*

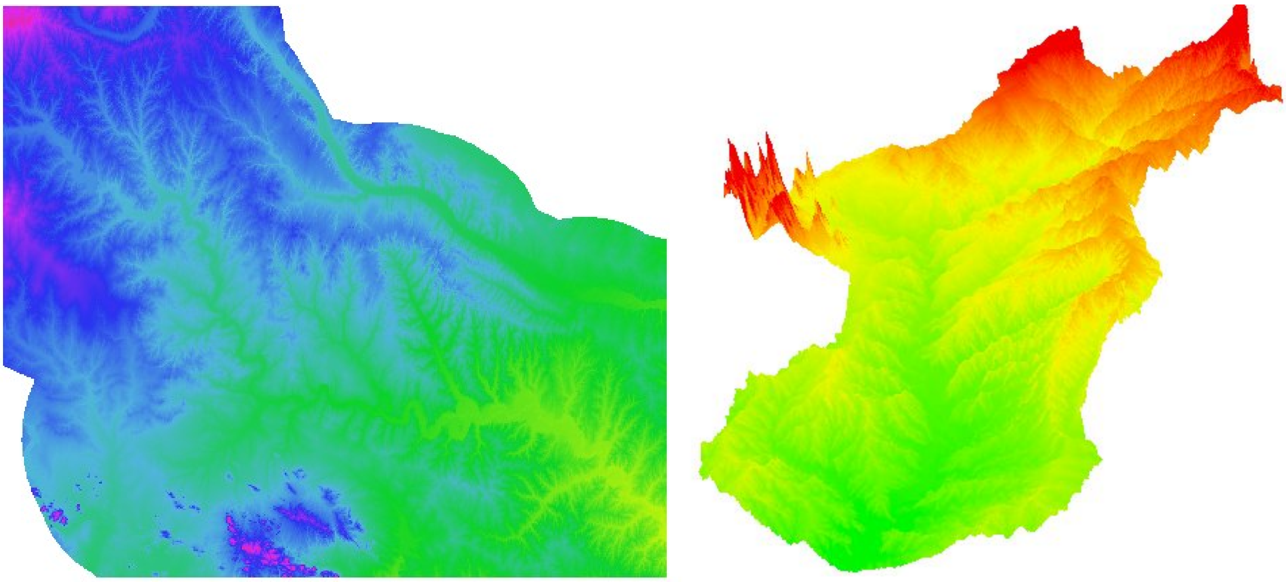


Figure 2-4 : Sample Raster DEM (Upper Washita Catchment)

Raster DEMs have a simple data structure that lends itself well to spatial analysis. For example calculation of area measurements is simply the sum of the included grid cells multiplied by the area of one cell. Conversely, calculation of the area of a polygon is considerably more complex and consequently, more computationally intensive in many cases. Raster DEMs have the further advantages of increasing availability due to their ease of sampling and interpolation from other terrain data sets.

One drawback of raster DEMs is that the source of the original spatial data cannot easily be ascertained by examining the DEM. For example, a raster DEM may have been remotely sampled or interpolated from various types of data. This information is important in any assessment of the DEM's suitability for topographic analysis or hydrologic modelling yet cannot be readily determined from the DEM itself.

Triangular Irregular Networks (TINs)

A TIN is a triangular network of data points of known elevation linked by triangular polygons. By design, the triangle vertices are meant to correlate to peaks and pits whereas the linear segments of triangles between the vertices should correlate to linear terrain features such as ridge or channel lines (Lee 1991). Triangles are chosen as the polygon vector data type to form the TIN because they are composed of three data points at each vertex of the triangle. Since three points define a rigid plane in space, these coordinates can be used to interpolate an elevation for any point that falls within the region defined by the x and y coordinates of the triangle vertices. A sample TIN DEM structure is depicted in **Figure 2-5**, the left side of the figure illustrates the triangles that have been constructed between the points of observed land surface elevation while the right side of the figure shows a 3D image of the landscape.

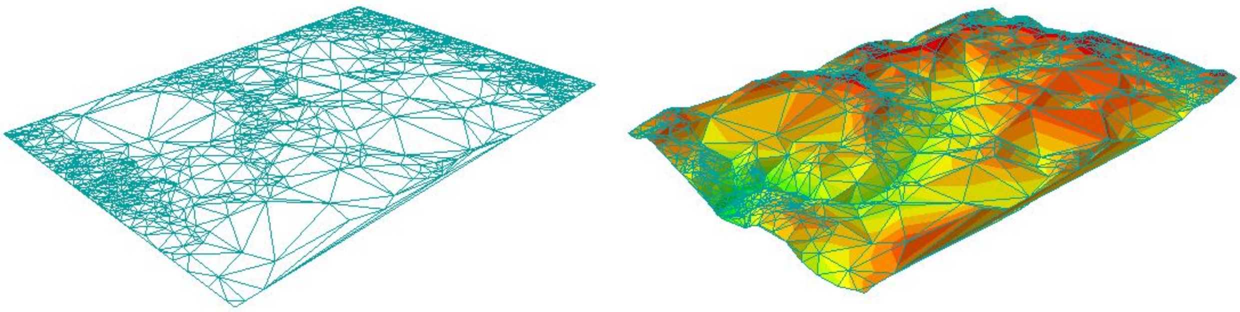


Figure 2-5 : Sample TIN DEM

One of the advantages of TIN DEMs is that they do not have a fixed scale and some sections of the DEM may be far more detailed than others. For example, as shown in **Figure 2-5**, the triangle density is much higher in particular parts of the DEM than in others. Hence, the land surface is more highly defined in these areas. The use of TINs for hydrologic modelling applications is also attractive because the steepest downslope flow path is a simple geometric function of the plane defined by the vertices of each TIN triangle. This is far simpler than deriving flow direction in a raster grid (*see page 49*). However, aside from flow direction calculations, hydrologic calculations on TINs are, in general, far more complex than on raster DEMs. Furthermore, treatment of TINs to resolve artificial sinks in a manner that is hydrologically consistent with the terrain is also considerably more challenging.

Development of TINs is usually performed using Delaunay Triangulation (Lee 1991) which attempts to join the spot heights using triangles that closely approximate equilateral triangles. This is achieved by requiring that 3 points form a Delaunay triangle if and only if the circle defined by them contains no other points. In this way, the triangles represent the broadest planes and assuming that the points exhibit good spatial characteristics, it should create a DEM that is geometrically representative of the terrain. An interactive demonstration of Delaunay Triangulation can be found at http://www.cs.cornell.edu/Info/People/chew/Delaunay.html. Unfortunately, Delaunay Triangulation does not take into account the elevation of the data points. As such, the formed triangles can be problematic, especially if the survey data is not well suited for this technique, such as point data from survey of cross-sections. This results in the necessity to introduce break lines into the triangle formation which are lines that no triangle is allowed to breach. Use of break lines can help create a good TIN from point data however it makes the process less automated, hence increasing time consumption and user subjectivity. That is, the resulting DEM may end up differently depending on the user who selects the location of break lines.

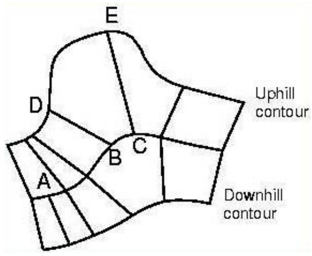
If TINs are developed from other data sources, such as contour data, further problems can be experienced. TINs developed from contours using Delaunay Triangulation can exhibit flat triangles since the contour polyline vertices are in close proximity and consequently, points of equal elevation are often chosen as the three triangle vertices for an individual triangle (Ware 1998).

Specialised DEM Structures

Raster DEMs and TINs are by far the most popular types of DEMs both in a general sense and in the specific context of automated terrain analysis for hydrologic modelling. However, as a result of the perceived drawbacks of these methods a number of alternative DEM data models have been proposed. Most of these were presented from a conceptual perspective but were found to be computationally impractical. However, two alternative DEM data models were developed further and should be mentioned in such a review. These particular DEM data models, the contour and flow line model and the quadtree DEM representation will be discussed in the following sections.

Contour and Flow Line DEM

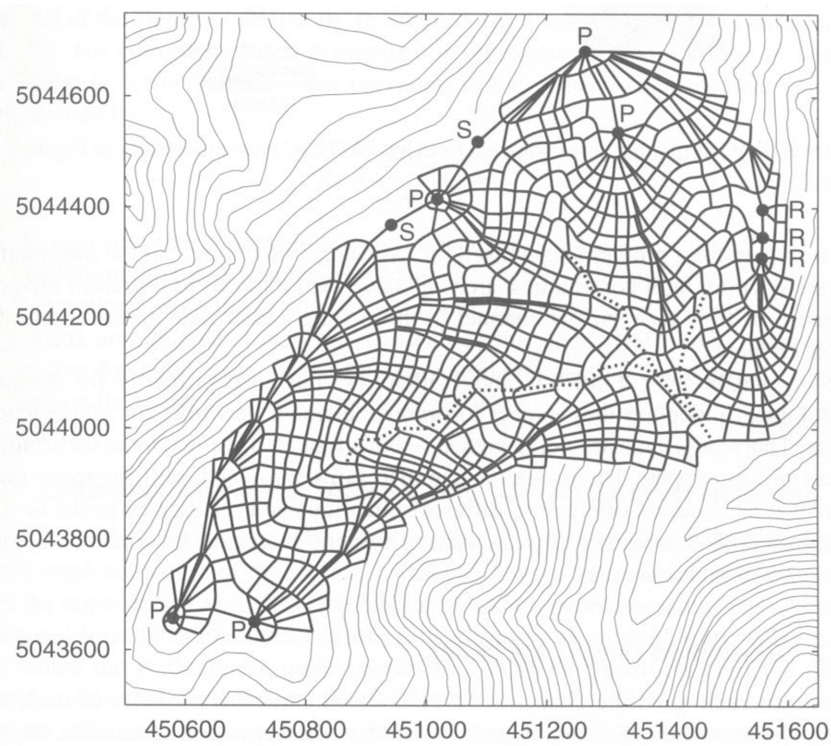
A specialised DEM structure for hydrologic applications is the contour and flow line model. This data model uses contours and flow lines to partition the catchment into flow elements that are aligned with the flow direction of the terrain. The advantages of this model are that flow elements may be of any size hence the model may have varying levels of detail in different regions which makes it data efficient in a similar manner to TIN DEMs (*see page 13*). However, unlike TIN DEMs, contour and flow line models are well suited to hydrologic applications since the flow element boundaries are aligned with the local flow direction creating high connectivity in the network and simple calculations of contributing areas (Wilson and Gallant 2000). The method of forming flow elements from contour data was first proposed by Onstad and Brakensiek (1968) who used their theories to manually partition catchments into connected flow elements as shown in **Figure 2-6**.



Source : Wilson and Gallant, 2000

Figure 2-6 : Development of a Contour and Flow Line Model

The flow lines that form the sides of the contour and flow line elements are formed using either shortest distance criteria (*BD in Figure 2-6*) or orthogonal flow criteria (*CE*), they may terminate (*A*) or initiate in a upslope direction (*B and C*) to maintain consistency of spacing of flow lines along the contour lines (Maidment 2002). Algorithms to help automate the tasks of setting up a contour and flow line DEM structure have been developed by O'Loughlin (1986) and Dawes and Short (1994). An example of a fully developed contour and flow line model using the TAPES-C software is shown in **Figure 2-7**.



Source : Wilson and Gallant 2000

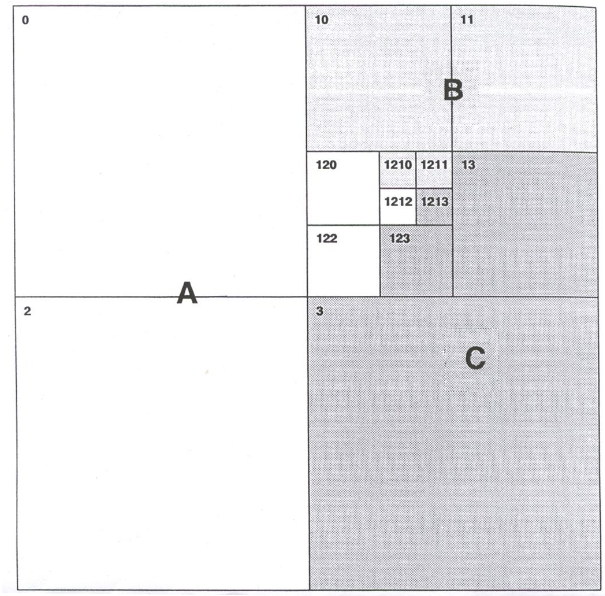
Figure 2-7 : Contour and Flow Line Model from TAPES-C

The algorithms developed to discretise a contour network into a contour and flow line element DEM require the user to specifically identify peak, saddle and ridge locations (*identified by P, S and R respectively in Figure 2-7*) or else the algorithms will fail (Wilson and Gallant 2000). Thus the process is yet to be fully automated and creation of a contour and flow line model can be very time consuming. Furthermore, it can be seen in **Figure 2-7** that the catchment boundary derived by the outer segments of the contour and flow line boundary is not a smooth shape and would deviate significantly to a catchment boundary generated by hand.

The lack of full automation in contour and flow line models and the consequential increased user subjectivity is a significant draw back of such models. It is also worth noting that the contour and flow line DEM structure is specific to hydrologic applications and cannot be used in other phases of an analysis where a DEM may also be required.

Quadtree DEM

The Quandtree data model attempts to overcome the scale-similarity disadvantage of raster DEMs by facilitating different sized grid cells within the one DEM. That is, raster DEMs have a rigid structure where each grid cell must have equal dimensions. As outlined previously, this can reduce the ability of the DEM to represent terrain features that are smaller in geographic extent than the spatial dimensions of the DEM grid resolution. Quadtree data models overcome this limitation by allowing square cells to be further discretised in certain areas of the DEM. For example, quadtree DEMs as implemented by the **Sp**atial **An**alysis **S**ystem (SPANS) can have up to 15 levels of quadtree discretisation (Ebdon 1992). A sample quadtree DEM with 3 levels of discretisation is shown in **Figure 2-8**.



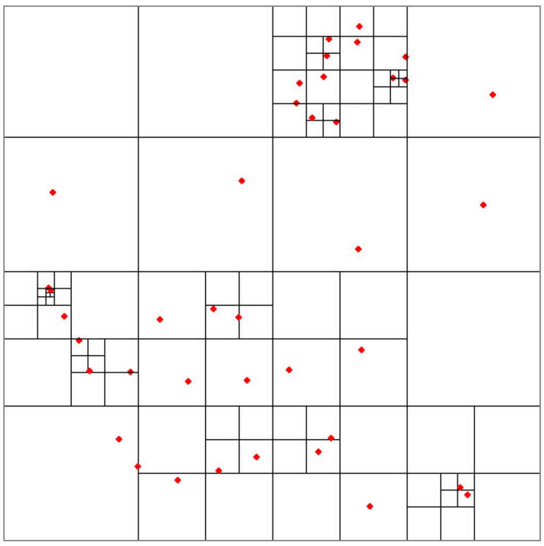
Source : Ebdon, 1992

Figure 2-8 : SPANS Quadtree Data Model

The quadtree data model can significantly improve the resolution of a DEM. For example if the base level cell size is 1000 metres x 1000 metres then the 15th level of quadtree discretisation would have a cell size of approximately 0.03 metres (1000×0.5^{15}). The corresponding savings in file storage requirements when using quadtree DEM structures as compared to raster DEMs can be up to 90% less in the case of terrain with large areas of sparse elevation data and small areas of highly detailed data (Ebdon 1992).

Cells in a quadtree DEM structure can be indexed by successive labelling of quadrants with the 0 (*NW*), 1 (*NE*), 2 (*SW*) and 3 (*SE*) integer values and adding further levels of detail onto the end of the integer identifier. For example, the quadtree cell 1213 in **Figure 2-8** is referenced by 1st level quadrant 1, 2nd level quadrant 2, 3rd level quadrant 1 and 4th level quadrant 3. An indexing format can be applied to enable relatively simple calculation of the location of the relevant quadtree cell for a given set of x, y coordinates and for other geo-spatial calculations.

A quadtree is generated by iteratively dividing spatial data into quadrants until every cell in the quadtree is homogeneous in terms of the elevation data it contains, or until a desired level of spatial resolution has been obtained (Ebdon 1992). This can be accomplished using various algorithms that have been developed to discretise DEMs into quadtree format from vector data, usually point source data. A sample development of a quadtree DEM from point source data is shown in **Figure 2-9**.



Source : Developed from http://njord.umiacs.umd.edu:1601/users/brabec/quadtree/points/prquad.html

Figure 2-9 : Sample Quadtree DEM from Spot Elevations

Despite the advantages of the quadtree data model, it has failed to become widely adopted or used in the GIS community. Both of the major GIS software producing corporations ESRI and Intergraph do not provide comprehensive spatial analysis support for quadtree models, and few DEMs are available in quadtree format. The author was unable to locate any sampled DEMs in quadtree format. The reasons for this lack of enthusiasm for the quadtree data structure are likely to be due to a number of factors. Firstly, many users maintain that the raster DEM disadvantage of required storage space that quadtree representations are attempting to overcome is a problem whose significance is dwindling into the future due to the exponential growth of low cost – high power computing. Secondly, while quadtree data models may reduce the required hard-disk space required for an analysis, they can increase the computational resources required for processing in the form of processor speed and RAM due to the increases in algorithm complexity and requirements for grid cell discretisation indexing protocols. Thus the enormous hard disk sizes available today may see the advantages of the quadtree model become somewhat redundant.

2.3.3 Suitability of DEM Types for Hydrologic Modelling

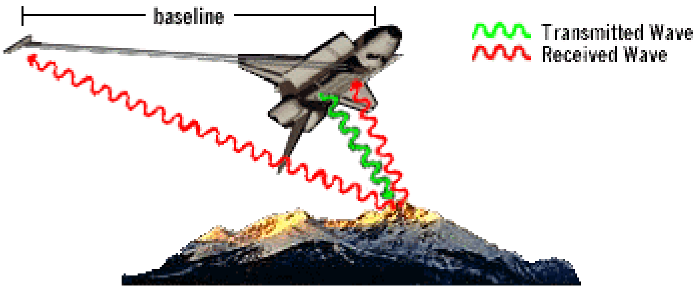
There are many advantages and disadvantages to the two main types of DEMs, raster and TIN. Ultimately, it depends on the application as to which DEM structure should be used. It is generally accepted that the principal advantages of each DEM format are level of detail of elevation data, and efficiency of data storage for raster and TIN format respectively (Goodchild and Lee 1989).

In the last decade, it has become apparent that a significant advantage of raster DEMs lies in their ease of derivation from the natural terrain surface. That is, modern terrain sampling techniques lend themselves better to development of raster DEMs than TIN DEMs. Consequently, the availability of raster DEMs is surging due to satellite techniques while the disadvantages of their use such as data storage requirements and other computational restrictions are becoming less important due to the rapid advances in computer technology. For example, it is relatively common now to apply hydrologic algorithms to raster DEMs with more than 50 million grid cells whereas processing of a grid of this size would have been impossible just a few years ago (Maidment 2002).

The availability of inexpensive raster DEMs for the globe is increasing. The USA is currently leading the world in providing free raster terrain data. The United States Geological Survey (USGS) currently distribute free seamless raster data for the entire USA called the National Elevation Data set (NED). The NED data has a resolution of 1 arc-second (*approximately 30 metres*) for the continental United States, Hawaii, and Puerto Rico and a resolution of 2 arc-seconds for Alaska. This data can be freely downloaded by any person. The USGS also distribute several other raster data sets including:

- Urban Areas High-Resolution Ortho-imagery
- National Land Cover Data set (NLCD) 1992
- Shuttle Radar Topography Mission (SRTM)
- MODIS NDVI Direct Broadcast

One of the most important of these is the Shuttle Radar Topography Mission (SRTM) which is a joint project between the National Imagery and Mapping Agency (NIMA) and the National Aeronautics and Space Administration (NASA). This project utilises radar interferometry where two images are taken from slightly different locations using a radar antenna in the shuttle payload bay and another radar antenna situated on the end of a mast positioned 60 metres from the shuttle bay as illustrated in **Figure 2-10**.

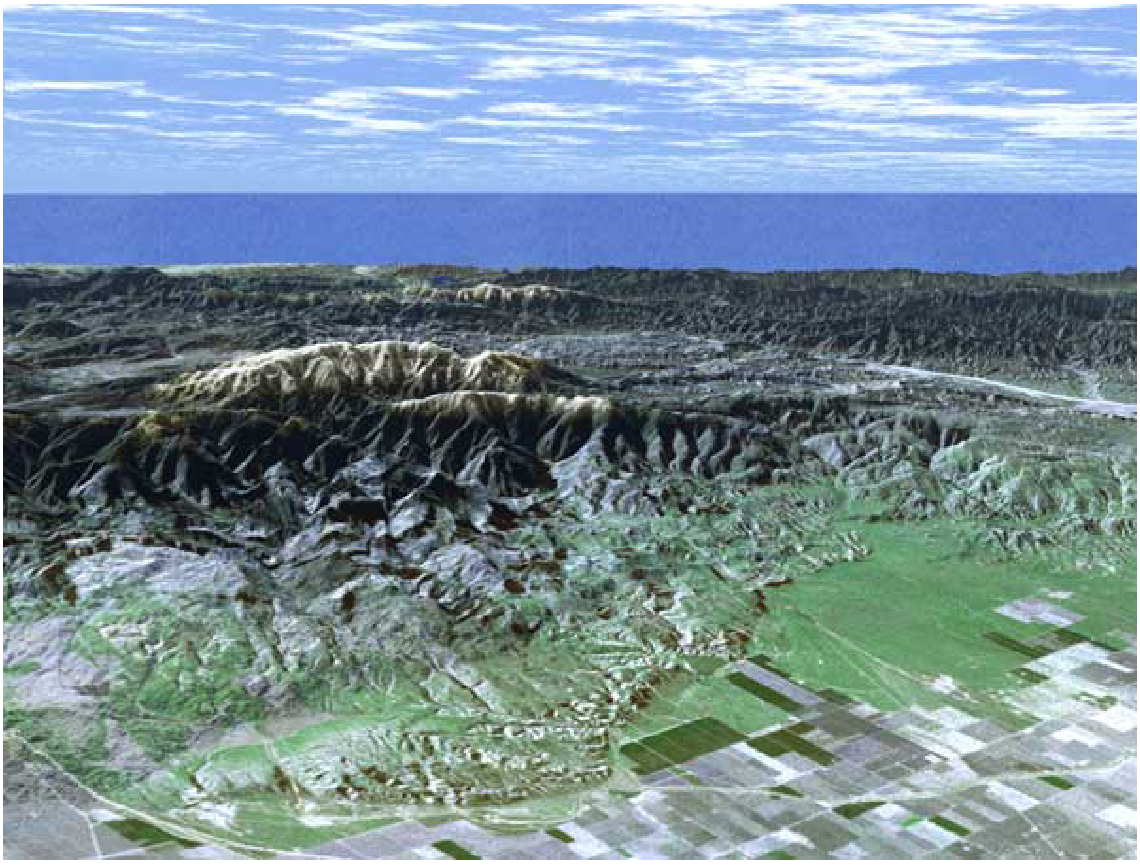


Radar signals being transmitted and recieved in the SRTM mission (image not to scale).

Source: http://srtm.usgs.gov/data/interferometry.html (17/9/2003)

Figure 2-10 : Radar Interferometry Technique

The shuttle based radar interferometry aims to produce raster DEM data for 80% of the Earth's land surface (*between 60° north and 56° south latitude*), with grid cells situated every 1-arc-second (*approximately 30 metres*) on a latitude/longitude grid. The vertical precision of the raster data should meet or exceed 16 metres. NASA claims this will result in the most accurate and complete raster data sets of Earth's surface that has yet been complied. An example of the raster DEM data after 3D rendering can be seen in **Figure 2-11**.

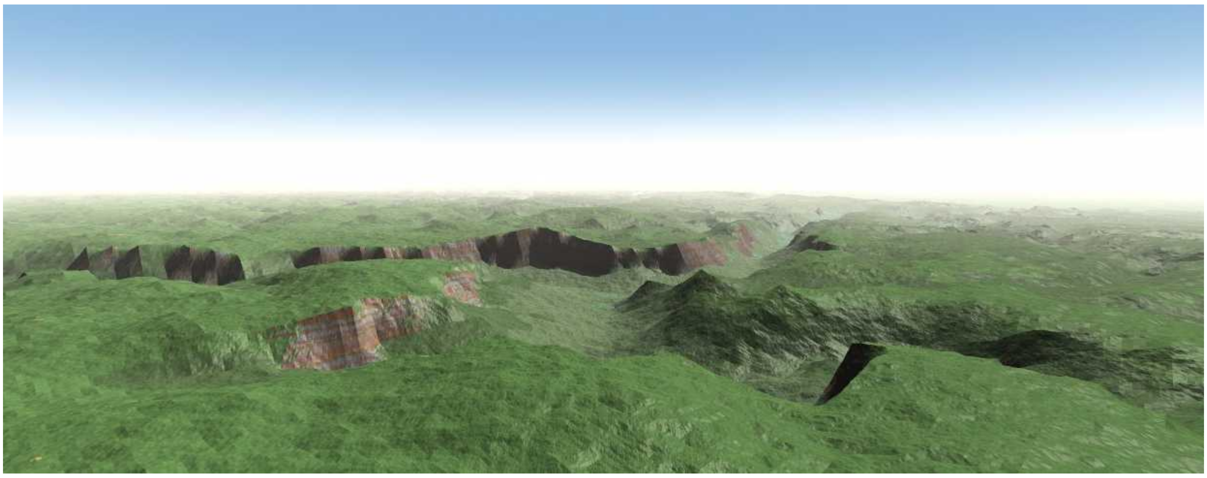


Source : http://srtm.usgs.gov/srtmimagegallery/mtpinos.htm

Figure 2-11 : SRTM Data for Mt. Pinos and San Joaquin Valley, California

Currently, 30 metre resolution SRTM data is only available for the USA and 90 metre resolution data is available for North and South America. However, radar images for the entire project area have been taken and raster DEM data for bulk of the Earth's surface will soon be released.

Legal requirements in the USA mandate that any data collected by government agencies may not be sold to the public for profit, hence all USGS data is freely available including SRTM raster data. Unfortunately, this is not the case in many other countries. Notwithstanding, other organisations have developed raster DEMs for their own countries including Australia. The Centre for Resource and Environment Studies in conjunction with AUSLIG has developed a 9 second (*approximately 250 metres*) national raster DEM for Australia. This product is available for purchase for $99. A sample of this raster DEM data is shown below in **Figure 2-12** after application of 3D rendering.



Source : http://cres.anu.edu.au/dem/grosval.jpg

Figure 2-12 : CRES DEM - The Blue Mountains, NSW

The growth in free or relatively low cost DEM data that has been evidenced in raster DEMs has not occurred for TIN DEM data. Hence, it appears that the popularity of raster DEMs both from an end-user perspective and a data development perspective will ensure their use as the dominant DEM data model for most applications. This is particularly true for hydrologic applications which use advanced geo-spatial algorithms that take advantage of the computational simplicity of the raster grid cell structure.

A further advantage of raster DEMs is that they can easily be interpolated from TIN DEMs by simply interpolating the elevation of the centre of a grid cell by its elevation on the planar surface of the TIN triangle it is located within. However, conversion from raster to TIN format is far more complex. To create a data efficient TIN from a raster DEM requires an algorithm to select 'surface-significant' grid cell elevations and develop triangles from these points. Although a number of algorithms exist to determine which cell elevations are 'surface-significant', all introduce approximation errors into the converted surface representation (Lee 1991).

Contour and flow line DEM structures and quadtree DEM data models have been developed in an attempt to overcome the drawbacks of TINs and raster DEMs. However, it must be said that they have not succeeded in gaining significant acceptance from within the GIS and hydrologic modelling community. In the case of contour and flow line models, this is largely thought to be due to the lack of automation for development of the model structure, and failure of the models to generate traditional delineated watershed boundaries. In the case of quadtree models, the primary advantage and reason for development of the quadtree structure is seen as redundant due to computational advances. Furthermore, the advantages of implementation of quadtree models are often considered less significant than the disadvantages of increased algorithm complexity. Finally, it is simply evident that sampled DEMs around the world are in general developed as raster data models. TIN DEMs are often employed for small to medium scale project-specific survey or aerial photogrammetry, however, larger scale applications developed for general purposes such as the SRTM sampling being conducted by the USGS (*see page 24*) is usually only produced in raster DEM format.

The most commonly stated disadvantages of raster DEM are the hard-disk space and RAM memory requirements that are required to process them. However, this disadvantage is becoming less significant due to the advances in computer technology. Hard-disk space and memory are becoming extremely cheap with many laptops coming standard with over 40 GB of hard-disk space and 1GB RAM memory for under $3000 AUD. This amount of hard-disk space could store a binary DEM (*with single precision*) with over 100,000 rows and columns (*100,000 rows * 100,000 columns * 4 bytes per value /* $1*10^9$ *bytes per GB = 40GB*). Such a DEM could describe the entire state of NSW with a cell size of around 10 metres. Furthermore, many geo-processing algorithms are now being designed in a RAM memory efficient manner to ensure efficient processing of massive grids. The r.terraflow algorithm in GRASS GIS (*page 90*) and RiverTools algorithm (*page 89*) can both process very large grids that exceed RAM capacity.

From the perspective of designing an application to solve hydrologic problems using DEM data, raster DEMs are far better suited. This is due to their computational simplicity, the amount of elevation detail, their wide availability and the asymmetric nature of raster-TIN conversion as outlined in the preceding sections. These reasons explain why the bulk of available software for these purposes (*see page 84*) are based on raster DEM analysis. As such, this review will focus on the raster data model and henceforth, DEM will specifically refer to a raster DEM.

2.4 DEVELOPMENT OF RASTER DEMS

DEMs may be developed from a variety of sources consisting of *sampled DEMs* or *interpolated DEMs*. Sampled DEMs are DEMs where each grid cell has a measured value. The measurement of each grid cell elevation may be based on aerial photogrammetry, satellite interferometry, laser survey or a number of other remote sampling techniques. Each of these methods of DEM sampling has its advantages and disadvantages, however a detailed discussion of sampling techniques is not relevant to this discussion. An important point that should be mentioned is that remotely sampled DEMs need to be filtered to remove surface anomalies (*termed noise*) from the surface profile. Surface noise can have both random and systematic components. Filtering may be achieved by a number of techniques including nearest neighbour sub-sampling (Bolstad and Stowe 1994), moving average in the spatial domain and low pass filtering in the frequency domain (Wilson and Gallant 2000).

2.4.1 Interpolation of Raster DEMs

Raster DEMs can also be developed by interpolation from topographic data in other types of data models. The choice of interpolation algorithm is important since it can have a significant effect on the DEM terrain attributes and errors, which can cause a follow-on effect in derived geo-spatial statistics or hydrologic calculations.

Interpolation from Point Data

Interpolation of DEMs from point data is usually achieved by an intermediate step where the point data is constructed into a TIN network which is then sampled at the centre of each raster grid cell to determine the elevation values for the DEM. As outlined in Section 2.3.2 (*page 11*), the effectiveness of the development of TINs from point data sources is highly dependent on the spatial configuration of the data points which is in turn, usually a function of the sampling methodology for deriving the point data source. Consequently, the suitability of a DEM developed from point based interpolation is more a function of the effectiveness of the points to TIN derivation and the original point configuration.

Interpolation from Contour (Vector) Data

The most common form of raster DEM interpolation is from vector contour data. Contours present a good data source for interpolation of DEMs because their alignment can provide more knowledge about the shape of the terrain surface than simply a string of points of common elevation (Wise 2000). For example, the curvature of contour alignments often indicates valley or channel locations (Mark 1986). Interpolation algorithms can be designed to take advantage of this additional information and improve the resulting topographic fitness of the DEM.

Wise (2000) identified four main categories for DEM interpolation algorithms, *point*, *profile*, *TIN* and *surface* based methods. Point based approaches treat the contour data as a string of points of common elevation and rasterise the contours into the DEM. After this process is complete, an algorithm is applied that examines the proximity of nearby assigned grid cells to develop an interpolated elevation for each unassigned grid cell. These methods do not take account of the additional information that is available in contour data.

Profile based interpolation algorithms attempt to model the surface in the area by assessing cross-sectional data cuts along various alignments, particularly those that closely approximate the direction of steepest descent. These methods are advantageous from the perspective of speed and simplicity, and also provide a good surface interpolation provided sufficient profiles are utilised to adequately define local slope.

TIN based methods employ triangulation to construct a TIN from the contour vertexes and then interpolate the unassigned grid cells by their position in their associated triangular plane. Unfortunately, these methods suffer the same problems of many TIN development algorithms where points located in the same contour line will be joined due to their close proximity creating invalid flat triangles that are not representative of the terrain surface of the region (Clark 1990). Procedures have been developed that have been successfully shown to correct these anomalous triangles (Ware 1998), however the resultant DEM is often a poor representation of the original contour data (Wise 2000).

The interpolation algorithm may also fall into the surface modelling category, where a 3D surface is attempted to be fitted to the surrounding data values and the grid cell is assigned an elevation based on interpolation from this surface. Surface fitting algorithms commonly use surface generating functions such as splines, polynomial patches or kriging (Matheron 1965). Surface based approaches can provide good approximations of continuous surfaces but they do suffer from a number of disadvantages. Firstly, they are commonly very computationally intensive. Furthermore, these algorithms can require close supervision because the complex shapes they are modelling can result in wide deviations from the original data points in areas that are not in close proximity to a data point. They may also produce anomalous terrain distribution in regions of low data sampling which can cause the resultant DEM to be less suitable for application in hydrologic modelling (Wilson and Gallant 2000). One method of overcoming the computational intensive nature of many higher order interpolation algorithms is local surface patches where surface fitting methods are applied to small areas of the DEM which are then smoothed together to form a continuous DEM. Mitasova and Mitas (1993) have obtained good interpolation results from contour data using bivariate spline functions in local surface patches. An advantage of this technique is that each local surface patch has continuous first and second derivatives which allow direct calculation of many topographic parameters such as slope and curvature (Wilson and Gallant 2000).

An important goal in many GIS aided hydrologic analysis is validation of the interpolation method by comparison with results generated using more traditional methodologies. These techniques are usually based on delineating catchments and subcatchments based on visual map interpretation using topographic maps. Assuming the user did not make a mistake when delineating a catchment, any automated technique must be able to closely match these results before it can be applied with confidence. As a result, from a quality assurance perspective, using DEMs that are derived from contour data can be seen to give the best chance for cohesion with traditional techniques because both approaches are based on the same data set rather than different and potentially conflicting terrain data sets.

2.4.2 Topographic Fitness

To ensure a DEM is suitable for use in hydrologic modelling it is important to consider the accuracy and reliability of the spatial information contained in the data model. This is particularly important for raster DEMs since the source data cannot necessarily be inferred from the DEM in order to assess its quality. The components of a raster DEM that affect its quality are vertical precision, errors and horizontal resolution. These will be discussed in the following sections.

DEM Errors

Errors in DEMs are a function of the DEM development technique. Sampled DEMs often exhibit artefacts from non-terrain objects such as dense vegetation or building roofs which artificially alter the sampled terrain surface (Rieger 1998). Interpolated DEMs tend to contain two main types of errors, errors in the DEM data itself and errors in the algorithm used in the analysis (Wise 2000). Errors due to the interpolation algorithm will be a function of the particular interpolation algorithm adopted and are discussed in Section 2.4.1 (*see page 29*).

The simplest measure of errors in DEMs is derived by the Root Mean Square Error (RMSE) which is calculated by examining DEM elevations corresponding to points of known elevation, as shown in **Equation 2-1**.

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}\left(Z_i^* - Z_i\right)^2}{N}} \qquad \textbf{(Equation 2-1)}$$

In **Equation 2-1**, N is the number of points of known elevation, Z_i^* is the *true* elevation and Z_i is the DEM derived elevation. However, RMSE errors tell a user little about the spatial distribution of errors in the DEM (Holmes et al. 2000). Holmes et al. (2000) analysed 2652 differential Global Positioning Systems measurements and USGS 30 metre DEMs and found that although the average RMSE was low, local errors could be high and exhibited a spatial correlation. Furthermore, derived topographic parameters such as slope and aspect have been found to compound systematic errors in a DEM (McKenzie et al. 2000).

Other methods of quantifying the error in a DEM include mapping the fractal properties of DEMs to reveal sampling artefacts and interpolation anomalies (Polidori et al. 1991) or assigning individual cell error distributions as a function of the derived global error measurements (Fisher 1993).

Vertical Precision

Vertical precision is the level of detail to which elevation values are sampled or recorded, whichever is the limiting factor. The vertical precision of a DEM can also have a significant impact on its fitness for hydrologic analysis. Thompson et al. (2001) in a comparison of topographic parameters derived from DEMs with differing vertical precision found that reducing vertical precision produced a large proportion of points with zero slope and zero slope curvature, in addition to a corresponding number of steeply sloping and more highly curved areas.

Horizontal Grid Resolution

Horizontal resolution of a DEM refers to the dimensions of an individual grid cell. Prior to use of a DEM for hydrologic modelling it is important to ensure that the resolution of the DEM is adequate to represent geographic features of a scale that will significantly affect the hydrologic properties of the catchment. Martz and Garbrecht (1993) found after analysis of an 84 km^2 watershed in south-western Oklahoma, USA that DEMs should have a grid cell area that is less than 5% of the network reference area (*mean area draining into individual channel network links*) to delineate channel drainage attributes within an accuracy of ± 10%. Thompson et al. (2001) compared terrain attributes and results from raster based quantitative soil-landscape models at different horizontal resolutions and vertical precisions. They found that reducing the horizontal resolution of the DEM produced shallower slopes on steep regions of the DEM, steeper slopes on flatter regions of the DEM, smaller ranges in curvatures, larger catchment areas in upper catchment regions and smaller catchment areas in lower catchment areas.

Despite the observed deficiencies in utilising DEMs with excessively coarse resolution, it should not be assumed that the highest resolution available should be used for every application. Firstly, it is important how the higher resolution DEM was derived. If it was interpolated from a lower resolution DEM without the use of any additional 'real' data, then the DEM does not actually include any extra information and any resulting perceived improvement in results is debatable. Secondly, sampling DEMs at increasing resolution leads to an increase in the level of DEM noise, which is where adjacent cells have different values as a result of sampling anomalies or insignificant undulations in the topography. Utilising 'noisy' data in hydrologic applications usually requires the data to be smoothed which can forfeit the perceived advantage of the higher resolution DEM as well as introducing other errors associated with the smoothing algorithm (Woodcock and Strahler 1987). Finally, the use of very high resolution DEMs may imply an accuracy that cannot realistically be expected from the subsequent algorithms and hydrologic models which may be applied.

2.4.3 Effect of Resolution, Precision and Errors

Several studies have found that errors or deficiencies in the horizontal resolution and vertical precision of a DEM can propagate through many derived parameters ultimately effecting hydrologic calculations such as runoff hydrographs (Kenward et al. 2000; Baxter 1993). Kenward et al. (2000) compared results generated from two coarse 30 metre resolution DEMs of varying quality (*one from the USGS National Elevation Data set and the other derived from interferometric processing of Spaceborne Imaging Radar-C*) and found that mean annual predicted runoff volumes were 0.3% and 7.0% larger for the USGS and SIR-C DEMs, respectively.

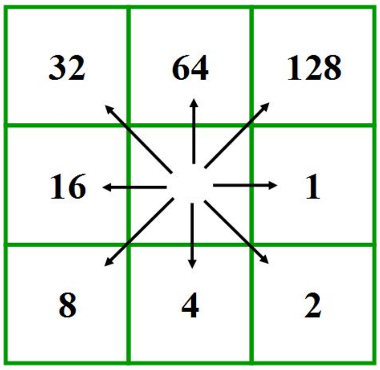
Horrit and Bates (2001) investigated the scaling effects of the LISFLOOD-FP model from a hydrologic and hydraulic perspective. Models of resolution 1000 to 10 m were investigated and compared against satellite observations of inundated areas and ground measurements of flood wave travel time. The maximum performance was reached at 100m and no further improvement was observed after this time. However, predicted flood wave travel times were found to be strongly dependent on DEM resolution. Hence, this study would suggest that DEMs used for hydraulic modelling may need to have a higher resolution and vertical precision than those required for hydrologic modelling.

A number of techniques may be used to assess the quality of a DEM. Generation of contours and comparison to source data (*if the DEM was interpolated from contour data*) provides a good qualitative check on the interpolation fitness. Other qualitative techniques use charting and display of shaded relief calculations and other topographic attributes (Wilson and Gallant 2000). As outlined previously, the Root Mean Square Error (RMSE) can be applied to test the DEM against a separate set of points of known elevation (Wise 2000). Frequency distributions of elevations and other topographic attributes can also be generated to assess the quality of DEMs. For example, frequency histograms of elevation for DEMs developed from contour data often illustrate a frequency bias towards elevations of the raw contour data since during the contour rasterisation process many cells were assigned to the elevation of the contour data. Smoothing algorithms can be employed to overcome these elevation frequency anomalies for DEMs interpolated from contour data (O'Callaghan and Mark 1984; Tarboton et al. 1990).

2.5 GENERIC HYDROLOGIC ANALYSIS OF RASTER DEMS

The basic process of hydrologic routing on raster DEMs involves tracing flow from all cells within the catchment through downstream cells until ultimately leaving the DEM. Cell flow paths that intersect with designated subcatchment outlet positions are recorded as being part of the associated subcatchment region. This is usually accomplished by creating additional raster grids storing flow directions and flow accumulation values for each cell in the DEM. To illustrate these principles the simplest (*and most common*) methodology will be examined. This method is the D8 flow routing algorithm as implemented by the Arc Hydro – Arc GIS application.

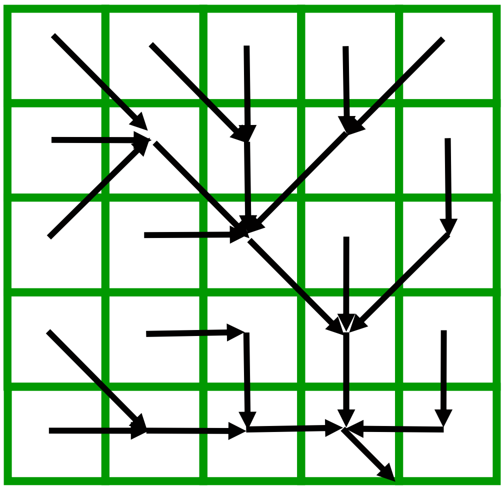
Firstly, flow direction for each cell is encoded into a raster grid structure identical to the DEM except the cells hold values associated with flow direction rather than terrain elevation. This matrix is commonly termed the *Flow Direction Grid* and is common to most single direction flow routing algorithms. For the D8 method, each cell in the flow direction grid is encoded with one of eight values (*assuming the cell is not a flat or pit cell*) corresponding to which neighbouring cell receives flow from the cell and its upslope neighbours. Different software applications have different conventions, Arc Hydro flow direction encoding is shown in **Figure 2-13** .



Source : Adapted From Tarboton 2002 (Presentation at Symposium on Terrain Analysis for Water Resources Applications, The University of Texas at Austin, December 16-18).

Figure 2-13 : Arc Hydro D8 Flow Routing Encoding

From this point, the flow direction grid can be represented as a connected network enabling calculation of a *Flow Accumulation Grid* which records the number of cells that form the contributing catchment for the cell. Conventions differ as to whether the flow accumulation grid should record the flow contribution draining to the cell, or from the cell. If the former convention is applied, cells with no upstream contributing area will have a flow accumulation value of 1, as opposed to 0 if the later convention is used. ESRI's Arc Hydro product uses the later convention. A networked representation of the flow direction grid and the corresponding flow accumulation grid can be seen in **Figure 2-14**.



0	0	0	0	0
0	3	2	2	0
0	0	11	0	1
0	0	1	15	0
0	2	5	24	1

Source : Adapted From Tarboton 2002 (Presentation at Symposium on Terrain Analysis for Water Resources Applications, The University of Texas at Austin, December 16-18).

Figure 2-14 : Networked D8 Flow and Accumulation Grids

Raster cells that are within catchments can be calculated based on upslope calculation from an outlet cell and stream alignments can be calculated based on a Stream Area Threshold (SAT). This technique designates cells as stream cells when their flow accumulation value exceeds a set minimum threshold (*see page 65*). Many more processes can be applied to undertake a hydrologic analysis such as stream network derivation, raster to vector conversion of catchment polygons and generalised parameter extraction, however, they are all dependent of the basic flow routing and flow accumulation principles.

Prior to applying flow routing and accumulation algorithms to raster DEMs, it is necessary to ensure the spatial distribution of DEM elevation values enables flow routing over the entire catchment of interest to be applied. Usually, algorithms must be employed to adjust a DEM prior to application of flow routing and accumulation algorithms, this process is termed hydrologic conditioning.

2.6 HYDROLOGIC CONDITIONING OF RASTER DEMS

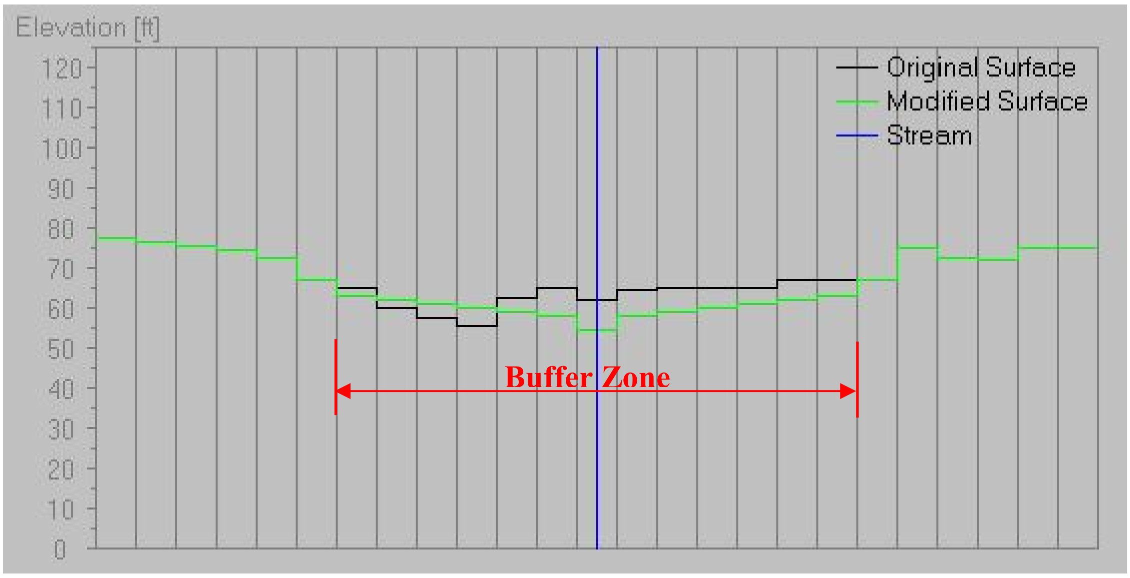
Hydrologic conditioning of a DEM consists of ensuring the major flow paths are represented in the DEM and that flat and pit cells are adequately resolved so as not to cause problems with the flow routing algorithm by creating spurious sinks.

2.6.1 Drainage Enforcement

Drainage enforcement and other hydrologic conditioning procedures are techniques imposed on a DEM to ensure that flow can be traced from all cells within a catchment to the catchment outlet without being hindered by problematic flat or pit cells (*sinks*). Specifically, drainage enforcement usually involves using an observed vector stream network (*blue lines of topographic maps*) as source data for an algorithm which ensures that these major flow paths are preserved in the DEM. Drainage enforcement may be employed as an ancillary algorithm applied after DEM interpolation, or some researchers have incorporated it into the actual interpolation algorithms. Hutchinson (1989) developed a system for generating a stream network from source data during the interpolation phase and using this network simultaneously to remove flats and pits from the interpolated data set, thus ensuring drainage connectivity in the resultant interpolated DEM. However, most drainage enforcement algorithms are applied following DEM interpolation and alter DEM elevations to ensure drainage connectivity.

Certainly, this approach is more generally applicable since most of today's DEMs are sampled DEMs and do not require application of interpolation algorithms.

As part of the development for the Arc Hydro tool set for ArcGIS, the AGREE method of DEM surface conditioning was developed. This method consists of three steps to use a vector stream layer to force drainage over a DEM. Firstly, the elevations of grid cells underlying the stream layer are lowered by a set increment. Secondly, a buffer is created on either side of the stream lines and elevations of cells within the buffer are adjusted so linear drainage is enforced throughout the buffer area towards the stream line. This may involve raising or lowering cell elevations, or both. Finally, the elevations of cells directly underlying the stream line are lowered by an additional amount. A chart illustrating the effect of the AGREE algorithm is shown in **Figure 2-15**.



Source : Adapted from http://www.ce.utexas.edu/prof/maidment/gishydro/ferdi/research/agree/agree.html

Figure 2-15 : AGREE Algorithm for Drainage Enforcement

The AGREE method has the advantage over traditional stream burning algorithms of creating a graduated cross-section that is more representative of the expected topography than a DEM with simply one line of cells burnt into the terrain. However, the method does not explicitly force drainage to follow the vector stream network to the outlet. The method may allow sinks to exist within the catchment if the actual cells along the stream lines do not always decrease in a downstream direction. Furthermore, the combined effect of the initial stream burning and final stream burning (*Stages 1 and 3*) can cause a significant drop in elevation between the original DEM and the AGREE DEM for cells along the stream lines. For example, in **Figure 2-15**, the AGREE algorithm has caused an elevation change of at least 5 metres for the stream cells. This may be more than is required for other stream burning techniques and could cause a resulting bias in calculated geo-statistics and slope calculations.

2.6.2 Flat and Pit Cells

Remotely sampled DEMs and interpolated DEMs will usually have a number of grid cells that are of equal or lower elevation than their neighbouring cells (*neighbouring cells may be the 8 surrounding cells or 4 adjoining cells depending on the adopted flow routing algorithm*). These flat or pit cells will cause flow routing algorithms to fail as drainage direction at these cells will be unable to be assigned. A number of algorithms have been developed to treat these cells and ensure flow routing can be applied. However, it is important to examine the source of flat or pit cells prior to adoption of a specific treatment approach.

Source of Flat and Pit Cells

Flat and pit cells may result from errors in the DEM sampling or interpolation technique or due to insufficient horizontal or vertical precision. For example, a DEM that is recorded to 1 degree, which translates to about 70 metres in the x coordinate and 90 metres in the y coordinate, will record streams with a gradient of 1% or less as flat grid cells since the vertical precision of these DEMs is rounded to the nearest metre (Jones 2000). Furthermore, horizontal DEM resolution may create flat and pit cells if a stream alignment is situated near the grid cell boundary of two or more cells. In such a situation the sampling point of each cell (*located at the centroid of the cells*) may fall on the stream banks which can be equal, or in many environments higher than the surrounding floodplain. Consequently, parts of the stream alignment may not be represented in the DEM and may be flat or elevated areas.

DEMs may also exhibit truly flat areas such as lakes or dams which can create problems in drainage direction assignment. Turcotte et al. (2001) points out that these areas should be treated separately from spurious flat and pit cells because they are not sampling or precision based errors rather they are real terrain attributes that should be considered as part of the drainage network.

Treatment of Flat and Pit Grid Cells

The method adopted for treating flat and pit cells should be considered in light of the source of the flat and pit cells as well as the ultimate goal of the terrain analysis exercise. If the purpose of the analysis is to delineate catchment and subcatchment boundaries then flat and pit cells need to be treated to enable flow to be successfully routed from all points within the catchment to the catchment outlet. However, if the analysis purpose is a geo-statistical or geomorphologic analysis then assignment of a more accurate estimation of revised elevation becomes more crucial than a topologically realistic derivation of drainage direction at the location of the flat and pit grid cells.

Some algorithms treat flat and pit cells separately whereas other algorithms consider them as identical problems. Many algorithms fill pit cells to the elevation of their lowest elevation neighbour, thus transforming them into flat cells, and then applying a flat cell treatment algorithm to the new group of flat cells. For the purpose of hydrologic modelling and watershed delineation, not all algorithms actually modify the flat cells. In fact, the most popular treatment algorithm (*adopted in the Arc Hydro ArcGIS product*) modifies DEM elevations for pit cells only (*converting them to flat grid cells*) and then only modifies the flow direction grid values at the location of the flat cells rather than altering DEM cell elevations. This algorithm was developed by Jenson and Domingue (1988) algorithm *(J&D Algorithm*). The J&D algorithm first fills pit cells to the elevation of their lowest neighbour, transforming them into flat cells. Following this, an iterative procedure is applied where flow directions for flat cells are assigned towards any neighbouring cells that have assigned flow directions. These neighbouring cells may be non-flat cells with calculated flow directions or flat cells assigned flow directions by the algorithm in a previous iteration.

Unfortunately, the J&D algorithm has a number of important disadvantages. Firstly, the DEM treatment is inconsistent, elevations of pit cells are modified where flat cell elevations are left unaltered. Considering the source of these anomalies is likely to be the same, the approach seems theoretically flawed. It is also apparent that filling of all pit cells or closed depressions involves introduction of systematic errors into the DEM. Pit cells and closed depressions in sampled or interpolated DEMs result from both underestimation and overestimation errors. Hence, filling all pit cells introduces a systematic error into the DEM based on the implicit assumption that all pit cells are underestimation errors (Martz and Garbrecht 1998).

Additionally, application of the J&D algorithm leaves the DEM in a form which contains flat cell flow anomalies that can make it unsuitable for other terrain analysis processes. More importantly, in large flat areas which are often due to DEMs sampled with low vertical precision the algorithm tends to create parallel flow paths which can bias flow path length and drainage density calculations (Martz and Garbrecht 1998; Tribe 1992).

Martz and Garbrecht (1998) proposed a method to overcome these disadvantages based on an iterative routine for assessment of the terrain surrounding flat cells and re-forming the topography into a V-shaped profile (*similarly to the AGREE method*). A breaching algorithm was also employed to avoid the implicit error involved in filling all pit cells. However, researchers have found this algorithm still tends to produce significant parallel flow paths (Jones, Richard 2000).

Smoothing algorithms have also been proposed by various researchers to eliminate flat and pit cells (O'Callaghan and Mark 1984; Tarboton et al. 1990). Although these approaches have been demonstrated to be successful at removing many arrangements of flat or pit cells, they tend to indiscriminately flatten real landscape curvature and introduce systematic errors into hill-slopes (Rieger 1988). Furthermore, Baxter (1993) found that smoothing introduced significant errors into hydrologic calculations later performed on the DEM.

Other algorithms designed to treat flat and pit cells have come from weighted graph optimisation theory. The most successful of these approaches is the Priority First Search (PFS) breaching algorithm developed by Jones (1998). This algorithm uses accepted weighted graph approaches to find an optimum drainage path from each flat or pit cell. This path will represents the optimum solution to a priority function which evaluates the flow path elevation gain, ultimate downslope gradient and flow path length. After an optimum drainage path has been found, the algorithm linearly interpolates cell elevations between the flat or pit cell and the outlet cell along the optimum drainage path in order to breach the flow obstruction. This algorithm has the advantages of treating pit and flat cells in an identical and consistent fashion and also creates drainage networks of a realistic fractal nature, avoiding the parallel flow path problems of earlier algorithms (Jones 1998).

2.7 FLOW ROUTING ON RASTER DEMS

Flow routing refers to the process of tracing flow from an individual grid cell through all downslope cells within a DEM. There are numerous algorithms available to perform flow routing on raster DEMs which can be categorised into two groups, *single direction* and *multiple direction* flow routing algorithms. Single direction flow routing algorithms only allow flow to pass into one of a cell's neighbouring cells whereas multiple direction flow algorithms allow flow to pass into two or more of the cell's neighbouring cells.

2.7.1 Single Direction Flow Algorithms

Single direction flow algorithms are the most commonly applied algorithms due to their relative simplicity. However, there are a number of available single direction flow algorithms that have a range of advantages and disadvantages.

D8 Method

The most common and simple technique is the 'D8 method' by Fairfield and Leymarie (1991), sometimes called the 'Eight Direction Pour Point Method.' The D8 method assigns flow to one of a cell's eight neighbouring cells based on which of these cells represents the steepest downslope descent path. This cell is determined by calculation of gradient between the cell elevations and distance between the cell centroids. Thus the lowest elevation neighbouring cell is not always selected since diagonal neighbours have a longer distance measure in the denominator of the gradient calculation.

As outlined in Section 2.5 (*see page 39*), the D8 method has been adopted in the majority of GIS aided hydrologic modelling software available including the Arc Hydro extension package for ArcGIS, distributed by the world's leading GIS software providers ESRI (Environmental Systems Research Institute).

The D8 method has a number of limitations which are well documented and accepted by the scientific community (Fairfield and Leymarie 1991; Tribe 1992; Rieger 1992; Costa-Cabral and Burges 1994). Firstly, the algorithm suffers from a bias towards flow in 45 degree increments, since flow direction is restricted to eight possible directions. In areas of consistent slope, this error can propagate in a downslope direction. Consider the DEM shown in **Figure 2-16**, this DEM exhibits a consistent aspect with a flow angle of 120° (*0° being North*). However, at every cell the D8 method needs to select one cell to allocate all of the flow from all upslope contributing cells and in this case it will select the south-eastern cell each time (*since the angle is closer to 135° than 90°*). The resultant error will increase in magnitude over the portion of terrain that has a similar angle.

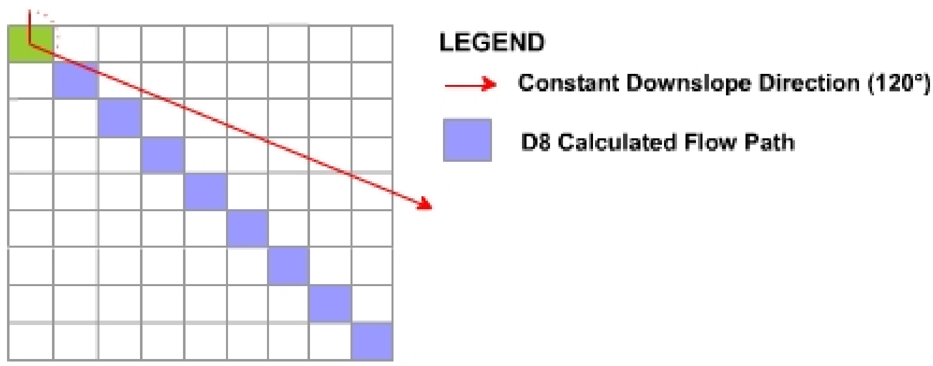


Figure 2-16 : D8 Error Propagation Downslope

Secondly, the D8 method fails to calculate contributing areas correctly in certain circumstances. For example consider the contributing area of the outlet cell illustrated in **Figure 2-17**, which displays the D8 calculated upstream subcatchment for a single cell. As shown, the combined area of the upstream cells is only 50% of the real contributing area of the cell (*as indicated by the black border*). This error varies from a factor of 0 (*in cardinal directions*) to 2 (*in diagonal directions*).

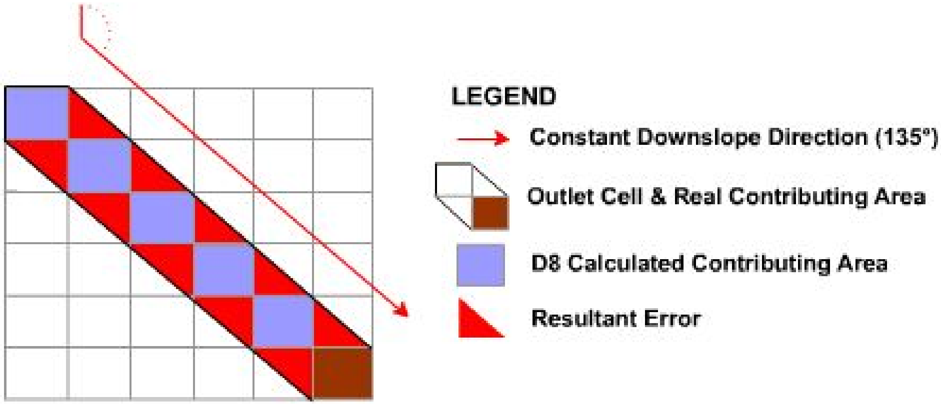


Figure 2-17 : D8 Contributing Area Calculation Error

Finally, the approximation of D8 flow directions to 45 degree angular increments can have the effect of both overestimating and underestimating flow convergence over a DEM. For example, assuming 0° is north, changes in flow direction that range between -22 to 22 degrees over a hill-slope (*a 44 degree range*) will be ignored by the D8 method since all cells will have their flow allocated to the immediately northward cell. In contrast, minor (*and possibly anomalous*) changes in flow direction between 22 to 23 degrees will effect the D8 flow direction for the cells, causing convergence when it is probably unnecessary. The effect of these problems is best shown in the stream networks that are generated used the D8 method, a sample of which is shown in **Figure 2-18**.

Figure 2-18 : Parallel Streams Resulting From D8 Method

Grid cells are designated as streams when the number of upstream contributing cells is greater than a specified value (*see page 65*). The stream network shown in **Figure 2-18** indicates many parallel streams exist in areas where contour curvature would suggest flow convergence should exist. It can also be seen that the D8 method's failure to represent convergence has artificially raised the calculated drainage density in the region.

Randomised D8 Method (Rho8)

Fairfield and Leymarie, (1991) attempted to overcome the major shortcoming of the D8 method by introducing a stochastic component into the algorithm. The Rho8 method assesses the error associated with the D8 calculated flow direction for a cell and then assigns flow direction for the cell using a probability function in proportion to the deviation of the D8 flow direction from the actual steepest descent path. Over a large section of topography this has the effect of producing more realistic flow path delineation. However, the process is stochastic and will produce a different flow path network and resultant subcatchment delineation every time the model is run. This is undesirable from both a conceptual and quality control perspective (Rieger 1998).

Aspect Driven Flow Routing

Lea (1992) proposed a flow routing algorithm based on routing flow along a vector path based on a local aspect angle developed from the eight surrounding grid cells. The advantage of Lea's (1992) method was that flow in each cell could adopt any angle from 0 to 360°. Entry and exit point coordinates where flow lines intersected with cell boundaries were modelling similarly to if flow was considered as a 'rolling ball' originating from the centre of the origin cell. Lea's method overcomes the D8 limitations of angular bias and drainage length bias, however, it retains the point source limitation of the D8 algorithm (Costa-Cabral et al. 1994).

2.7.2 Multiple Flow Direction Algorithms

Multiple flow direction algorithms attempt to overcome the failure of single direction flow algorithms to represent divergent flow. Specifically, once flow from a number of cells has converged using single direction flow algorithms then this flow cannot diverge. Multiple flow direction algorithms achieve flow diversion by having the capability to distribute flow from a cell to two or more of its neighbouring cells.

In order to apply a multiple direction flow algorithm each cell must be split into proportions that drain to two or more of the downstream cells. Beasley et al. (1980) proposed dividing cells by a line in the slope direction through a corner point. These two areas were then routed to the two neighbouring cardinal grid cells. Wolock and McCabe (1995) used the elevation difference between a cell and its eight neighbours to route proportions of the upstream contributing areas to the downslope cells. This approach has also been applied by Rieger (1992 & 1993) using only the 4 cardinal neighbours. However, over time a number of algorithms have grown to be the most commonly applied multiple direction flow algorithms. These algorithms will be discussed in the following sections.

Multiple Direction D8 Method (FD8)

The FD8 method proportions flow to all downslope neighbours using the formula shown in **Equation 2-2** (Wilson and Gallant 2000).

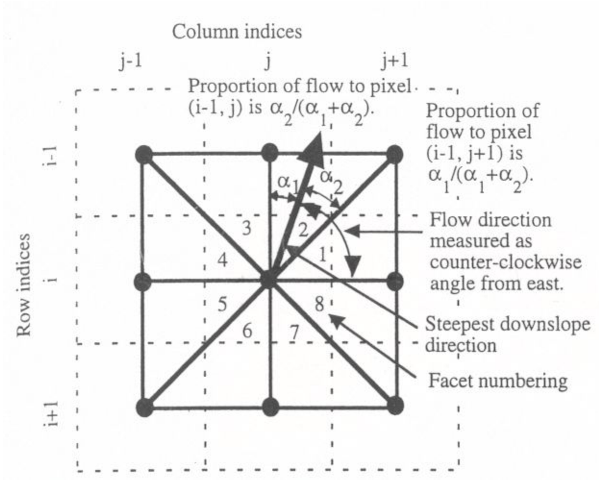
$$F_i = \frac{\max\left(0, S_i^v\right)}{\sum_{i=1}^{8} \max\left(0, S_i^v\right)} \qquad \textbf{(Equation 2-2)}$$

In **Equation 2-2**, S_i is the slope from the central node to neighbour *i* and *v* is a positive constant. Freeman (1991) found that setting $v = 1.1$ gave the best fit for flow divergence over a conical surface, however, other researchers suggest that higher values (*6-8*) of *v* give more realistic results in natural situations where less divergence is desired (Holmgren 1994).

The algorithm usually produces excessive flow divergence in valley areas despite adjustments to the *v* parameter in **Equation 2-2**. Consequently, the FD8 algorithm is often replaced by the D8 algorithm when flow accumulation reaches a particular threshold, a technique called *'maximum cross-grading area'* (Wilson and Gallant 2000).

D∞ Algorithm

The D∞ algorithm was first proposed by Tarboton (1997). This algorithm is a multiple direction flow algorithm that proportions flow from each cell to two of its neighbours. Flow directions for the D∞ algorithm are developed by constructing steepest descent angles for each of the eight triangular facets formed by a 3 x 3 grid cell window around the cell of interest. A sample of a triangular facet calculation is shown in **Figure 2-19.** Each of the eight calculations are compared and the one that is associated with the largest downward slope is selected and adopted as the flow direction for that cell. Flow from that cell is then proportioned between the two cells used to form the selected triangular facet in accordance with the equations listed in **Figure 2-19**.



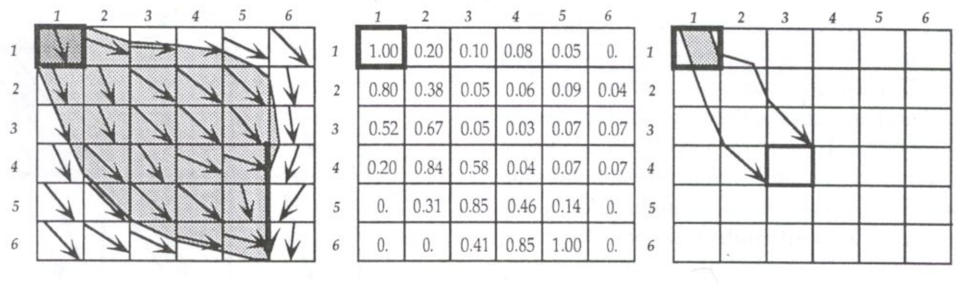
Source : Tarboton 1997

Figure 2-19 : D∞ Runoff Proportioning

Tarboton (1997) suggests that the D∞ algorithm is an effective multiple direction flow routing algorithm because it can represent flow divergence but does not excessively distribute flow since a maximum of two neighbouring cells can be allocated flow. Unfortunately, application of the D∞ algorithm to an individual cell can result in no flow being allocated to the cell of steepest descent. This can occur if the neighbours of the steepest descent cell have relatively high elevations and a pair of relatively low elevation cells are located in one of the other eight triangular facets.

Digital Elevation MOdel Networks (DEMON) Algorithm

The DEMON algorithm was introduced by Costa-Cabral and Burges (1994) in an attempt to overcome the problems associated with single direction flow algorithms, in particular the D8 method. The algorithm is aspect driven with flow directions for each cell calculated in a similar fashion to Lea's (1992) method. However, the DEMON algorithm does not assume that all flow originates from the centre of the origin cell and calculates a vector flow path for the grid cell vertices as illustrated in **Figure 2-20**.



a) b) c)

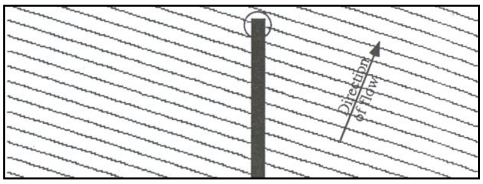
Source : Costa-Cabral and Burges 1994

Figure 2-20 : DEMON Stream Tube Algorithm

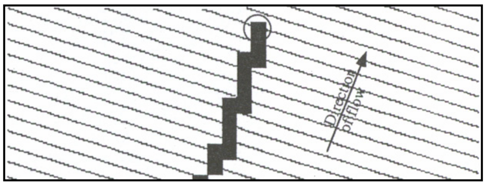
Figure 2-20 a) indicates how flow from cell 1-1 diverges and then converges over the DEM in accordance with the flow direction grid (*represented by the arrows*). Unlike the D8 method, the flow direction in each cell may adopt any angle (*similarly to Lea's method - 1992*). **Figure 2-20 b)** records the influence matrix for cell 1-1, note that cells 1-1 and 6-5 both have 1.0 influence values, since all flow from 1-1 passes through these two cells. The flow accumulation grid for the DEMON algorithm is derived by the addition of the influence matrix calculated for all cells in the DEM. The physical meaning of the value of 0.58 in the influence matrix of cell 4-3 is illustrated in **Figure 2-20 c)**.

2.7.3 Flow Routing Algorithm Analysis

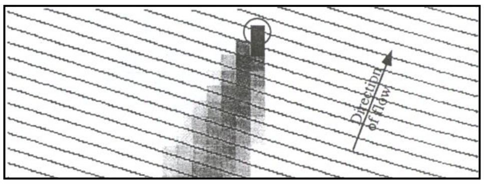
The widely adopted D8 method is accepted to give a poor representation of expected flow paths. As outlined previously, a number of other single and multiple flow direction algorithms have been introduced to overcome the disadvantages of the D8 method. Tarboton (1997) compared these algorithms during his development of the D∞ algorithm. The upslope contributing areas developed over a planar surface for a range of flow routing algorithms are shown in **Figure 2-21**.



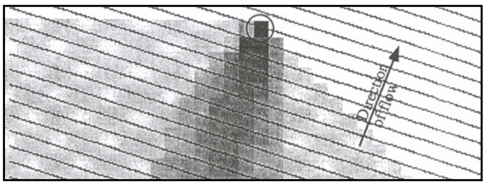
a) D8 Algorithm



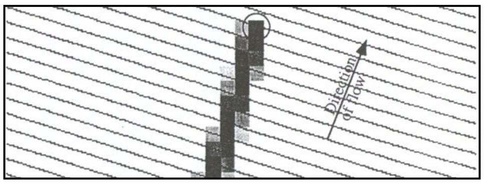
b) Lea's (1992) Method



c) D∞ Algorithm



d) FD8 Algorithm



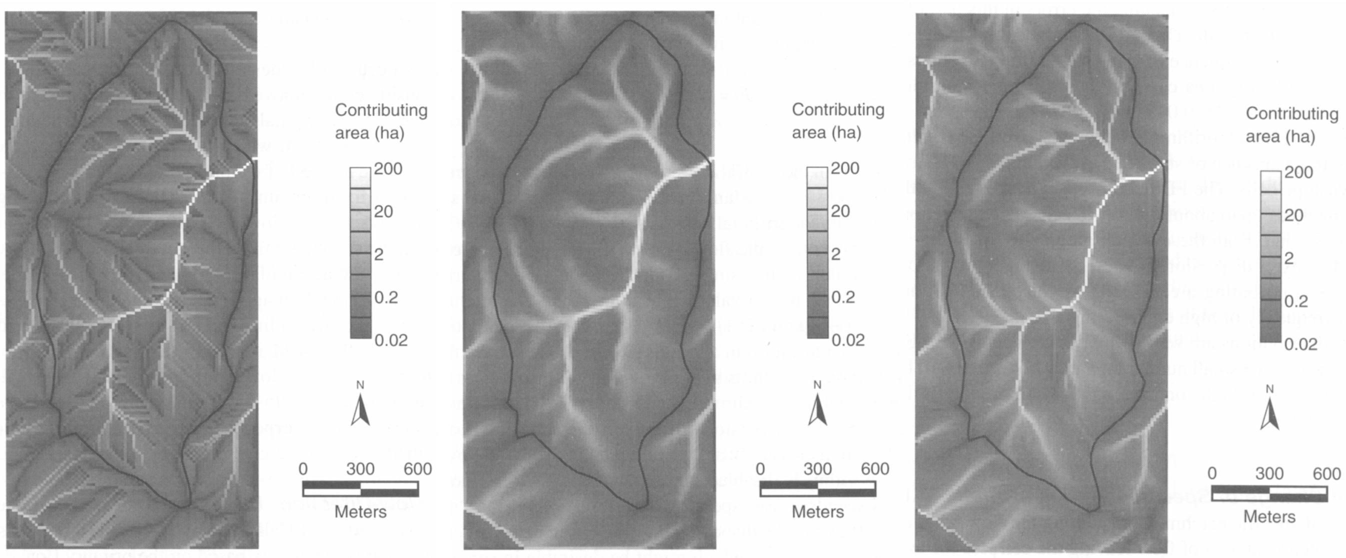
e) DEMON Algorithm

Source : Adapted from Tarboton, 1997

Figure 2-21 : Upslope Contributing Areas by Flow Routing Algorithm

The flow direction bias of the D8 method can be clearly seen in **Figure 2-21 a)** as well as the excessive divergence of the FD8 method in **Figure 2-21 d)**. Flow divergence in the D∞ algorithm is also excessive considering all flow paths should travel perpendicular to the illustrated contour lines. Lea's (1992) method and the DEMON algorithm perform best in this test with a realistic narrow catchment that accurately represents the flow direction of the planar surface.

The characteristics of the calculated flow accumulation grid are also highly dependent on the flow routing algorithm that is adopted. Wilson and Gallant (2000) compared the flow accumulation properties of a number of flow routing algorithms, their results are indicated in **Figure 2-22**.



a) D8 Algorithm b) FD8 Algorithm c) DEMON Algorithm

Source : Adapted from Wilson and Gallant, 2000

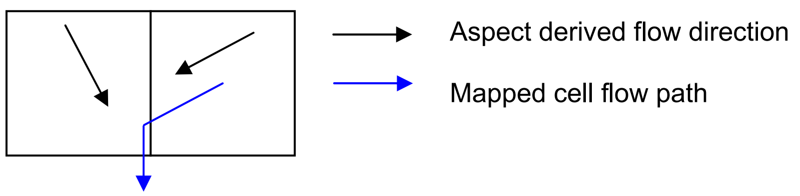
Figure 2-22 : Flow Accumulation Comparison of Flow Routing Methods

It can be seen in **Figure 2-22** that the D8 method produces artificial looking flow accumulation characteristics that exhibit the flow direction bias and parallel flow paths that are typical of this method. The FD8 method produces a much smoother flow accumulation grid but the excessive representation of divergence can be clearly seen. The DEMON algorithm produces a better representation of the expected flow accumulation characteristics with less divergence and it also does not exhibit the problems associated with the D8 method.

A number of other studies have also compared single flow direction algorithms with multiple flow direction algorithms. (Quinn et al. 1991; Desmet and Govers 1996; Wolock and McCabe 1995). In general the multiple flow direction algorithms have been found to produce smoother flow accumulation matrix surfaces that are perceived to be more representative of terrain. However, as shown in **Figure 2-21** and **Figure 2-22**, it has been noted that multiple flow direction algorithms tend to over-spread flow and cause divergence where it is not physically likely to occur. As a consequence, many researchers have proposed using multiple flow direction algorithms in hill-slope areas and single flow direction algorithms in channel and higher curvature areas (*maximum cross-grading area*). Furthermore, unless a maximum cross-grading area is applied when using multiple direction flow algorithms, a connected vector stream network cannot be developed, which is important for most hydrologic modelling purposes (Rieger 1998).

Despite the encouraging performance of Lea's (1992) method and the DEMON algorithm (Costa-Cabral and Burges 1994) as illustrated in **Figure 2-21**, flow directions in both of these techniques are based on the slope of a plane of best-fit through the elevation at each corner of the cell. These elevations are in turn based on the average of the four surrounding cell elevations for each cell corner point. However, since three points absolutely define a plane, in most cases the best-fit plane cannot match all four points and an approximation must be made. This can result in flow directions being assigned towards cells with higher elevations. Furthermore, the use of aspect in calculation of downslope drainage direction can be questioned from a theoretical perspective. Tarboton (1997) suggests that cells of higher elevation than the cell for which flow direction is being calculated are not relevant since a rain drop will not flow upstream, it should only be concerned with the elevation of downslope cells.

To reduce the impact of such flow anomalies, Lea (1992) suggested that when aspect derived flow direction caused flow to converge at cell boundaries then the vector flow path should be allowed to cross into the other cell by a nominal amount (*0.000001*) and then travel parallel to the boundary as shown in **Figure 2-23**.



Source : Adapted from Lea 1992

Figure 2-23 : Treatment of Flow Anomalies Proposed by Lea (1992)

Although the adjustment shown in **Figure 2-23** will solve many of the anomalies that can result from aspect driven flow directions, flow paths are still permitted to flow towards, and even cross into, cells of higher elevation (Lea 1992; Tarboton 1997). These problems are also evident in the DEMON algorithm which is based on the same aspect driven principles. In fact, the code for the DEMON algorithm cannot be obtained because it is "*hard to program and full of special cases*" (*M. Costa-Cabral, persona communication 1995 cited in Tarboton 1997*). These special cases and consequential inconsistent computational approach is a significant drawback of these methods.

As a result of the different approaches to flow routing and the unique disadvantages of each method, no unique flow routing algorithm can be judged to be superior to all others. It is more important to be cognisant of the implications of the choice of flow routing algorithm on results. In many cases, the choice of flow direction algorithm can have a relatively minor effect, particularly when so many other significant uncertainties exist in such an analysis. For example, Wolock and McCabe (1995) found that slight differences between single and multiple flow direction algorithms where found when comparing TOPMODEL model efficiency and simulated flow paths, however, these differences disappeared when the model was calibrated by adjustment of subsurface hydraulic parameters.

However, some conclusions may be drawn from the flow routing algorithm analysis. The D8 algorithm can be categorised as the poorest approach to flow routing, with the Rh08 algorithm producing slightly better results, yet incorporating an unwanted stochastic component. The FD8 method seems to be the poorest multiple direction flow routing algorithm due to its exaggeration of divergence and increased user subjectivity since the user must select a *v* coefficient (*see Equation 2-2, page 55*). Lea's (1992) method and the DEMON algorithm perform best, however, they both suffer from approximating flow direction from a best-fit planar surface between 4 points.

2.7.4 Subcatchment Delineation

Subcatchment delineation is the process of determining the boundaries of subcatchment drainage area(s) for the region of interest. For example, a user may wish to delineate a single catchment or a networked set of hundreds of subcatchments based on intersections in a calculated stream network (*see page 65*). A subcatchment area is delineated by determining the boundary of the set of cells associated with a subcatchment outlet. These cells are mapped from the DEM by using a flow routing algorithm to trace the flow from a cell and determine which outlet it passes through.

The D8 algorithm has the computational advantage of being able to progress backwards from the outlet to determine the subcatchment boundaries, which is considerably faster than the conventional process of calculation of flow direction, accumulation and outlet identifying raster grids. This is possible due to the simplicity involved with limiting flow to 8 possible directions. More advanced single flow direction algorithms require processing of the entire raster grid to determine subcatchment boundaries. As outlined in Section 2.7 (*see page 49*), the choice of flow routing algorithm can have a significant impact on flow path mapping. These flow path mapping deviations can have a follow on effect in the generation of subcatchment boundaries and subsequent calculations of area and other topographic attributes. Furthermore, use of most multiple flow direction algorithms can render generation of subcatchment boundaries impossible unless grid cells are split. This occurs because these algorithms proportion flow to two or more of a cell's downslope neighbours. As such, individual grid cells may contribute flow to more than one subcatchment.

2.8 GENERATION OF STREAM NETWORKS

Development of stream networks is important for calculation of hydrologic parameters such as drainage density and shape. Stream networks should be a collection of vector lines with an inherent connectivity. That is, each line segment should have an assigned flow direction which provides hydrologic connectivity throughout the network.

The process of stream network development first requires the identification of channel heads which are points where streams will originate and flow in a downslope direction. From a theoretical perspective channel initiation occurs wherever the processes of incision dominate over the more diffuse processes of rain splash, bioturbation and creep (Prosser and Dietrich 1995). Two main theories have been proposed to use this relationship to help predict the locations of channel heads. The first proposes that the transition to channelised flow occurs when lateral perturbations in a surface are unstable in the presence of overland flow so that initial scour is self perpetuating (Smit and Bretherton 1972; Kirby 1980). The implications of this theory are that some degree of sediment transportation occurs in all runoff generating areas. The second theory states that resistance to erosion caused by soil cohesion and vegetation represents a definite threshold level below which the resistance prohibits the processes of incision and sediment transport from occurring.

2.8.1 Computational Methods for Stream Network Generation

Both of the aforementioned models for channel initiation present significant challenges for application on DEMs for generation of derived stream networks, yet, the latter is easier to implement than the former. Consequently, the concept of channel initiation thresholds have become popular in DEM based analysis. Vegetation and soil cohesion data is rarely available at a scale that could be applied to determine channel initiation in DEM analysis. Hence researchers have looked toward derivative DEM parameters to serve as potential threshold criteria. Typically, channel initiation thresholds can be applied in the form of area, slope-area or contour curvature thresholds.

Channel initiation thresholds based on area and slope-area relationships both require the use of a flow routing algorithm to generate the stream network relationship. Hence, the choice of the flow routing algorithm (*see page 49*) is a complicating factor in assessment of the success of these methods. Almost all research done to date on channel initiation thresholds for area and slope-area relationship has utilised the D8 flow routing algorithm (*see page 50*) to develop the flow accumulation grid required for the stream network generation. Contour curvature based methods are attractive since they do not require a flow routing algorithm to be applied. However, they have other theoretical shortcomings and more significantly, practical restrictions on their application in DEM based analyses. These methods will be discussed in more detail in the following sections:

Constant Threshold Area Method

The simplest and most common method of generating a stream network is by combination of the aforementioned D8 method with the concept of a minimum support area required to initiate stream morphology (O'Callaghan and Mark 1984). This method treats all cells with a flow accumulation value greater than a Stream Area Threshold (SAT) as stream cells, and all others as non-stream cells. The stream cells may then be vectorised using a raster to vector conversion algorithm to establish a vector stream network. This enables calculation of conventional hydrologic geo-statistics such as stream lengths and drainage density. This is illustrated in **Figure 2-24**, which depicts a grey-scale shading of a sample D8 flow accumulation grid as well as the vectorised streams (*red lines*) as generated based on a user-designated SAT value.

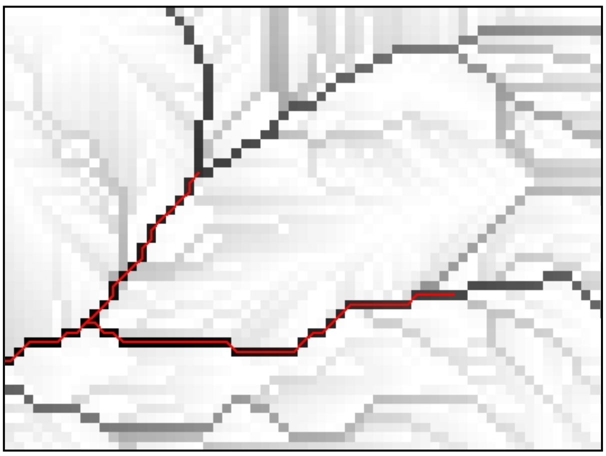


Figure 2-24 : Raster and Vector Stream Representations

The choice of SAT value has a direct influence on the resultant stream network. A lower SAT will produce a larger and more detailed stream network whereas a higher SAT will produce a more skeletal stream network. This is akin to examining hydrography mapped for the same catchment on topographic maps of different scales.

The choice of SAT value is often based of arbitrary judgement or visual comparison of the generated network with ‘blue lines’ from topographic maps (Zevenbergen and Thorne 1987; Morris and Heeredegen 1988; Gandolfi and Bischetti 1997). Some research have proposed quantitative methods of SAT determination such as Tarboton et al. (1991) who stipulated that geomorphologic laws including the power law of link slope with area (Flint 1974) and the constant stream drop law (Broscoe 1959) can be assumed to hold for generated stream networks similarly to field-surveyed stream networks. Although Tarboton presents strong evidence for his case and provides a good base for selection of a SAT value where no other basis for judgement exists, many researchers have found a poor correlation between stream networks generated using a single SAT and field survey (Mark 1984). This is most likely due to the use of only a single factor (*upstream contributing area*) in the channel head identification process.

The SAT can also be allowed to vary across a catchment or project area. For example, a SAT of 500 grid cells may be used in an area that is perceived to be more prone to local erosion and channel initiation where a SAT of 1000 cell may be used for a different area of the catchment which is considered to be more resistant to channel initiation.

Methods Considering Additional Properties

If a second factor is important in identification of channel heads then it is most likely to be slope. This was established by Montgomery and Dietrich (1988) and Dietrich et al. (1993) who pointed to a relationship between the SAT required to match surveyed stream networks with local slope immediately upstream from the channel. They proposed a power law to determine channel head locations as a function of local slope and flow accumulation. However, their efforts are yet to produce any significant practical improvements over the constant threshold area approach as any relationship between slope and channel initiation is most likely to be due to small erosional processes at a scale that prohibits accurate calculation from published maps and DEMs. This inferred conclusion is the result of apparent contradictions in work by Gandolfi and Bischetti (1997) and Montgomery and Dietrich (1989). The former of these researchers, in a comprehensive comparison between generated, field-surveyed and photo-interpreted stream networks, found no relationship existed between slope and channel initiation whereas Montgomery and Dietrich (1989) found a clear relationship when local slope was measured in the field. Furthermore, other research has found that relationships between slope and channel initiation seem to be catchment dependent and may be related to many other factors such as soil, climate and morphology (Gandolfi and Bischetti 1997).

Curvature Based Methods

Other proposed methods of stream network derivation explore development of a stream network based on exploration of critical contour curvatures. These methods do not utilise flow routing algorithms explicitly, rather networks are derived by skeletonising the DEM based on contours. In these cases, thresholds are based on contour curvature rather than SAT values (Meisels et al. 1995). An advantage of techniques based on these principles is that they are not dependent on the flow routing algorithm applied and are therefore not affected by its limitations, such as the deficiencies shown to occur using the D8 algorithm (*see page 50*). In a comprehensive comparison of stream networks derived from SAT techniques and critical curvature analysis, Ichoku et al. (1996) found that the fractal dimensions (*see page 76*) behave more consistently with respect to network extraction threshold variation with curvature based networks as compared to SAT based methods. They drew the conclusion from this data that curvature based methods produce more realistic stream networks because previous research has shown that, at a consistent scale, fractal dimensions have a direct relationship with detail (Strahler 1957; Horton 1942).

Despite these encouraging results, it is difficult to utilise contour curvature techniques with DEM data unless original contour data is available as a supplementary data source that is highly correlated with the DEM data. Many of these methods cannot be applied to remotely sampled DEMs and any advantage associated with their implementation is lost if contours are extracted from a DEM. This is because extracted contours have erratic shape (*particularly if extracted from a TIN network*) and the intricacies of curvature are not evident.

However, some methods for curvature analysis exist for use with DEM data where no contours are available such as those proposed by Peucker and Douglas (1975) who derived techniques to examine curvature as a local parameter by assessment of a cell and its eight neighbours. Their techniques involved determining surface-specific points such as peaks, pits, passes, ridges, ravines, slopes, breaks and flats by examining the changing gradient in a clockwise direction from the cell of interest. These techniques have been incorporated into some modern software packages (*TauDEM, see page 86*) and have shown some success at delineating channel networks (Tarboton 2003). However, these techniques are highly dependent on the DEM being 'topologically well behaved' (ie., *smooth neighbourhood correlation*) (Peucker and Douglas 1975). More importantly, to work well, the DEM needs to have quantised terrain elevations. That is, the elevations of the DEM should be in discrete increments, such as to the nearest metre, rather than accurate decimal values. This means that the DEM must be pre-processed or simplified which may remove accuracy and create flat and pit cells. Finally, since the method is not based on a flow routing methodology it is common that the network will not be able to be generalised in a hydrologically suitable stream network. That is, situations such as isolated stream segments and looped flow can be found in curvature based stream networks (Miesels et al. 1995).

2.8.2 Evaluation Methods

Methods of automated stream network generation are generally validated by comparison to blue line networks from topographic mapping. However, this method of comparison has been criticised. Firstly, blue line networks have been found to deviate significantly from field observations (Mark 1983; Coffman et al. 1972). These discrepancies are largely due to cartographical generalisation, where the cartographer selectively omits channels to simplify the form of the portrayed hydrologic element (Mark 1983). Furthermore, visual comparison of the compared networks is a subjective and qualitative process and it would be beneficial to develop a more quantitative method of comparison. Additionally, where these network are to be used for the purposes of hydrologic modelling it is perhaps more important to establish the cumulative effect of the stream network deviations on hydrologic parameters rather than the visual fit of the generated network.

2.9 HYDROLOGIC ANALYSIS

Whilst derivation of area, slope and other conventional topographic quantities are valuable attributes of DEM analysis techniques, they are not in themselves sufficient to adequately define the hydrologic properties of a catchment. The wide range of hydrologic models in use today demand a full spectrum of local and global, topographic and hydrologic parameters to be extracted from a DEM. Methods for extraction of these parameters will be discussed in the following sections.

2.9.1 Topographic Parameters

Local Topographic Parameters

Local topographic parameters are typically calculated on an individual grid cell scale. These include elevation, slope, aspect, flow direction and other variables that can be calculated from the 3 x 3 grid cell matrix surrounding each cell (*except those on the boundary of a DEM*). As described in previous sections, there are many methods of calculating these attributes that are dependent on the use of the subsequent data. For example, different methods of calculation of slope, aspect and flow direction exist as a function of the flow routing algorithm that is to be applied (*see page 49*).

Generalised Topographic Parameters

Generalised topographic parameters are values that can be calculated based on a subset of grid cells from the DEM. The subset of grid cells may be in the form of a geometric shape surrounding a cell of interest or based on cells within an identified subcatchment. Common generalised topographic parameters identified by Moore et al. (1991) include average vectored slope, area, shaded relief, frequency distributions, mean height of upslope area, mean slope of upslope area, mean slope of dispersal area, average slope over the catchment, maximum distance of water flow to a point in the catchment, mean length of flow paths to a point in the catchment, distance from a point in the catchment to the outlet, distance from highest point to outlet, slope profile curvature and elevation percentile (*proportion of cells in a user-defined circle lower than the centre cell*). These attributes may be calculated for an individual DEM cell (*eg., elevation percentile*) or a subset of DEM cells such as a subcatchment (*eg., area or average vectored slope*).

Application of Parameters in Hydrologic Modelling

These parameters can provide valuable insight for setup and calibration of a hydrologic model based on GIS data sets. For example, lumped hydrologic models can use generalised topographic parameters averaged over each subcatchment as a basis for assignment of runoff lag coefficients whereas models that are distributed over individual cells can use local topographic parameters, and generalised topographic parameters on an individual cell basis, as a foundation for assignment of hydrologic model parameters.

2.9.2 Stream Network Analysis

One of a catchment's hydrologic attributes that holds great potential to help explain hydrologic variability is stream network form. Kirkby (1976) found that even with drainage area and drainage density held constant, network topology can influence peak discharge by a factor of 200% and time to peak by a factor of 400%. The effect of a 200% deviation in peak flow could have a very significant influence of flood behaviour and flood extent mapping, and a 400% deviation in time to peak would dramatically influence evacuation and contingency planning as well as flood forecasting protocol. Thus, analysis of derived stream networks (*see page 66*) and their hydrologic form has real value for resultant hydrologic analysis, particularly in regions where limited hydrological data is available for calibration, or land-use changes have precluded its use as a valuable calibration data set.

The variability of peak discharge and time to peak calculations are accommodated in hydrologic models by lagging and runoff routing parameters that can be stipulated for individual subcatchments or catchments as a whole. For example, the Watershed Bounded Network Model (WBNM - Boyd et al. 1975) has a 'C' parameter which can be adjusted to reflect the rainfall response from each subcatchment. This is a simplified representation of the drainage network topology's effect on the hydrologic regime. Consequently, a more definitive understanding of stream network topology may result in a better understanding of the required adjustments to lag parameters, such as WBNM's 'C' parameter. A number of statistical quantities have also been demonstrated to be useful in hydrologic analysis as discussed in the following sections.

Fractal Nature of Channel Networks

Since fractals were first defined (Mandelbrot 1975) there has been debate regarding whether stream networks have a fractal nature. A significant body of work has now shown that most stream networks have fractal properties (Tarboton et al. 1988; Cheng et al. 2000; Phillips 1993; Moussa and Bocquillon 1996). Cheng et al. (2000) found that stream networks generally have space-filling properties and are free of geological constraints, however, differences between stream network forms in individual subcatchments can be related to topographic parameters. In particular, Cheng et al. (2000) found that stream density, slope and ratio of perimeter over area of drainage basins were related to individual fractal coefficient variance.

Horton / Strahler Geomorphologic Analysis

Horton (1945) made strong progress in the development of a quantitative understanding of geomorphology in his development of the Horton stream ordering system and its later revision by Strahler (1957). Strahler's revision of Horton's numbering system designated all uppermost tributaries as order 1. Where two 1st order streams combined a 2^{nd} order stream was created, where two 2^{nd} order streams combined a 3^{rd} order stream was created and so on, as shown **Figure 2-25**.

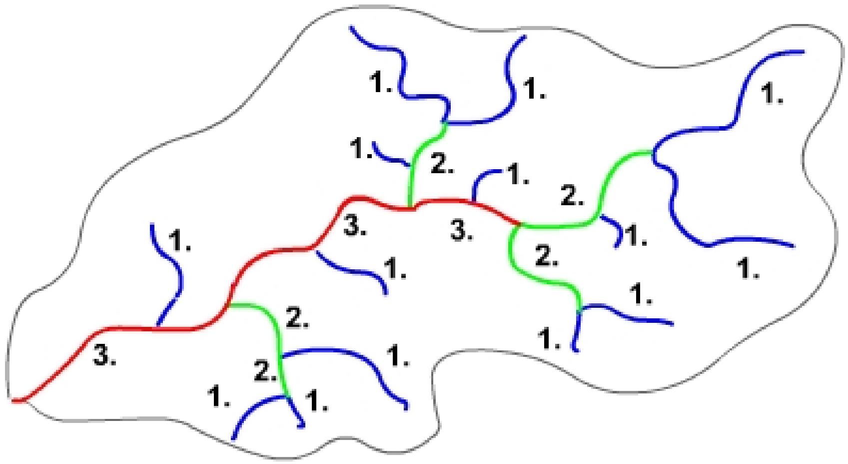


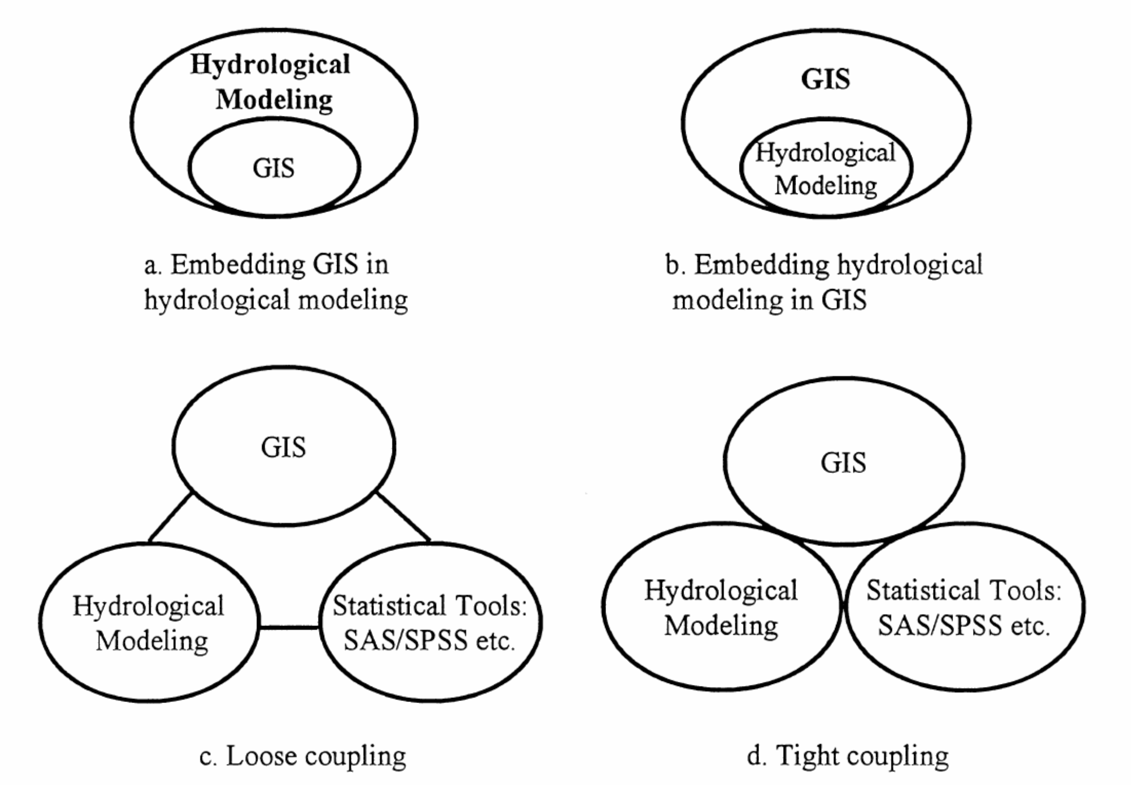
Figure 2-25 : Strahler's (1957) Revision of Horton Stream Ordering

Strahler found that the resulting networks shared common properties, most notably that a strong relationship could be shown between the logarithm of stream order vs the number of streams of that order. The slope of the resulting relationship is termed the bifurcation ratio (Strahler 1957). However Shreve (1966) demonstrated that most dendritic networks obey Horton's laws of drainage composition. The work of Shreve (1966) and Smart (1974) resulted in the formulation of the 'random' model which dictates that all topologically distinct channel networks of a constant magnitude are equally likely. A random model can generate a stream network population by assuming that a network is generated from its outlet and the probabilities of branching (p) and terminating at a source (q) remain constant throughout the network. If the random model is accepted empirically then it would suggest that channel networks are topologically random (Shreve 1966).

Einstein once said *"God doesn't play dice"*. Despite his particular reference to quantum theory in this case, his quote has become indicative of the readiness of research theory to adopt a stochastic approach to defining processes that defy conventional understanding. In essence, his words mean that nothing is random, a process may only appear random because it is dictated by forces that we don't fully understand or that occur on a scale that we cannot measure. Hence, it is unlikely that stream networks are truly random. Furthermore, regardless of the randomness of the evolution of such networks, their ultimate form can have a significant effect on their hydrologic rainfall response (Kirkby 1976). Consequently, any measure of topologic network form that can be used to differentiate between subcatchments in a hydrologic model may have valuable potential for assignment of rainfall response related model parameters.

2.10 COUPLING OF GIS WITH HYDROLOGIC MODELS

It has been observed in Australia and around the world that the influence of the increasing availability of GIS terrain data sets can be slow to propagate through towards a greater conceptual or quantitative understanding of hydrologic behaviour. A significant reason for this is poor compatibility between commercial GIS software and 'industry standard' hydrologic modelling computer packages. This is further complicated by significant disparity between largely internationally standard GIS techniques and highly country-specific approaches to hydrologic modelling. Integrating GIS and hydrologic modelling is seen as the best solution to these problems and is commonly termed *coupling*. Sui and Maggio (1999) identified four main categories of coupling between GIS and hydrologic models which are illustrated in **Figure 2-26**.



Source : Sui and Maggio 1999

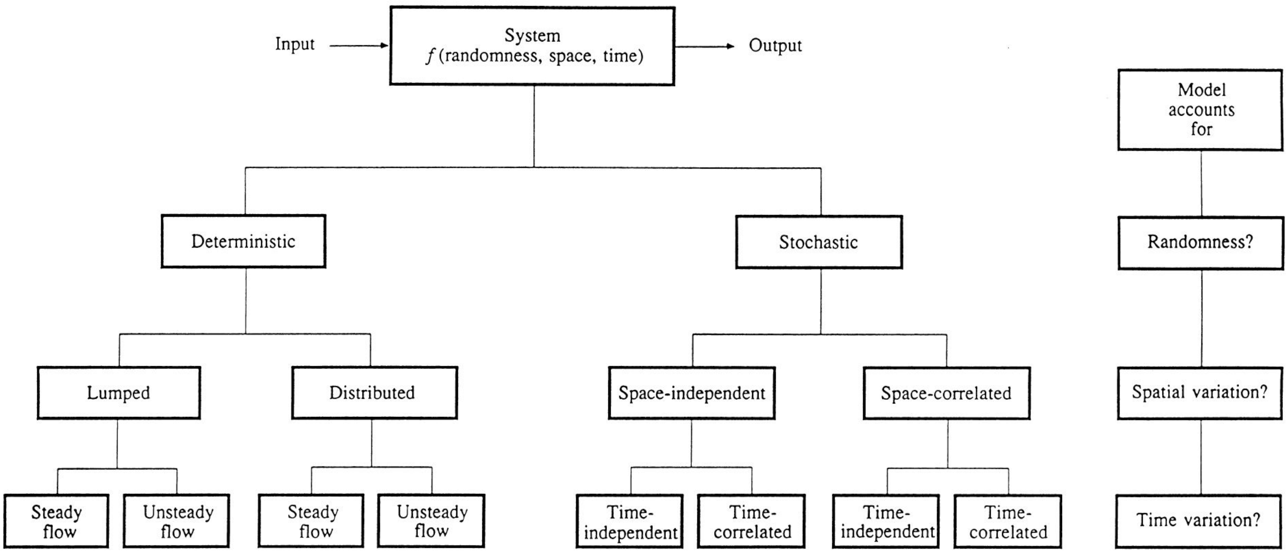
Figure 2-26 : Types of GIS – Hydrologic Model Integration

As shown in **Figure 2-26**, integration of GIS may occur in a number of ways including integration of the technologies into singular applications (*a) and b)*) or coupling GIS and hydrologic models using one or bi-directional data transfer (*c) and d)*). Where total integration is desired, GIS may form either the controlling entity in a combined GIS – hydrologic model, or may be a subset of the capabilities of a hydrologic model. Based on which of these integration regimes the user wishes to use, it is apparent that actual role of GIS in the process of hydrologic modelling may vary from total to virtually none. If the actual modelling is not undertaken by the GIS then the hydrologic model may be coupled either `loosely' using conversion protocols for data transfer, or `tightly' where the GIS and hydrologic model share a common data structure and both interact with the same database (Clark 1998). Maidment (1993) has extrapolated on this work to provide a more detailed analysis of the practical implications of coupling between GIS and hydrologic models. He suggests that the link between GIS and hydrologic models could range over the following spectrum:

- Simplification of hydrological modelling principles and application from within GIS;
- GIS based derivation of hydrologic model parameters (*ie., using GIS as an input device for hydrologic models*);
- Hydrologic modelling from within GIS (*provided time frames or temporal generalisations are used instead of time-series*);
- Full real-time 'tight' bi-direction coupling between GIS and hydrologic models.

Despite the allure of the high-tech full linkage approach to integration of GIS and hydrologic modelling, the evaluation of such coupling approaches should not be based on the extent to which the GIS is `in control' of the modelling process, rather which option provides the user with maximum flexibility and ultimately facilitates the most objective hydrologic analysis (Clark 1998). In practise, most GIS have not been developed to undertake specific engineering or scientific purposes (Goonetilleke and Jenkins 1996). Hence, adoption of GIS software as a controlling entity can mean that the limitations and capabilities of the GIS software are imposed on the study as a whole, or the coupling is forced to be put aside and parts of the analysis undertaken independently of the GIS (Goonetilleke and Jenkins 1995).

Furthermore, significant fundamental differences in the representation of space, time and randomness between GIS and hydrologic models pose potential barriers to full integration of GIS and hydrologic models. Chow et al. (1988) identified eight distinct groups of hydrologic models based on their specific approaches to conceptualisation of space, time and randomness. The hierarchy of these models are shown in **Figure 2-27**.



Source : Chow et al. 1988

Figure 2-27 : Taxonomy of Hydrologic Models

The varying conceptualisations of space, time and randomness within hydrologic model can create significant problems for any serious attempt at full coupling with GIS (Sui and Maggio 1999). GIS frameworks are setup from a cartography perspective with a layer orientated approach, which forces a temporally fixed segmentation of geographic features (Raper and Livingstone 1995). Furthermore, current GIS conceptualise space and time based on Newtonian mechanics where space is forced to a planar representation and time is conceptualised as discrete slices rather than a continuum (Gatrell 1991). This is in distinct contrast to how many hydrologic models conceptualise time and space, particularly stochastic models which represent variable values at each point by a probability distribution. Such random fields cannot be easily represented by current GIS conceptualisations of time and space (Sui and Maggio 1999).

Current GIS and hydrologic models also have differing fundamental approaches to the representation of motion. GIS usually adopt a Lagrangian view of motion where the focus is on the moving component whereas hydrologic models usually utilise an Eulerian approach where the focus is on a fixed reference frame through which the motion occurs. According to Maidment (1993), these differing conceptualisations of motion can make GIS integration with hydrologic modelling very challenging. Sui and Maggio (1999) suggested that as a result of these conceptual barriers, current attempts at coupling of GIS and hydrologic models can do little more than "*putting old wine in new bottles - An improved means for unimproved end*". That is, the underlying science is not improved, rather simply a more technologically efficient technique is created. However, on the other hand, it can be argued that without the computational simplicity provided by coupling much of the bulk data transfer, computational number crunching and brute-force sensitivity analysis that coupling facilitates would be left undone.

In practice, the distinction between 'loose' and 'tight' coupling can be transparent to the user and consequently of little relevance. Tight coupling is often difficult to achieve since the file formats for GIS software applications are often un-published proprietary format (*such as the MapInfo Table format*) or are strongly dependent on the GIS software version. Furthermore, loose coupling can be constructed in an efficient manner where the user is unaware of the coupling methodology and can seamlessly transition from the GIS software to the hydrologic model. This is usually achieved by macro languages that automatically create files that may be directly opened by the complementary software.

In the case of Australia, at the time of writing, the most common rainfall runoff models applied in Australia were the Runoff Analysis & Flow Training Simulation - RAFTS-XP (Goyen and Aitken 1976), Watershed Bounded Network Model – WBNM (Boyd et al. 1975), RORB (Laurenson and Mein) and URBS (Laurenson, Mein & Carroll). None of these models include capabilities for automated hydrologic or topographic analysis of raster DEMs and the author could find no evidence of available coupling procedures between GIS used in Australia and most of these hydrologic models. Consequently, it would seem reasonable to assume that the potential of automated terrain analysis software to help derive and calibrate hydrologic models has gone largely unrecognised to date in Australia. It is certainly the author's experience that most rainfall runoff models in Australia are setup manually by hand-delineation and map-interpretation techniques using topographic maps, and best-guess approaches to hydrologic parameter estimation, particularly in the absence of quality calibration data.

2.11 HYDROLOGIC TERRAIN ANALYSIS SYSTEMS

The previous sections have aimed to outline GIS fundamentals and the available algorithms for DEM based hydrologic analysis. However, while a theoretical description of algorithm design is important, such research cannot propagate through to application in real projects until the algorithms have been implemented in software packages. It is not until this step has been accomplished that the true success of an algorithm can be judged from both and accuracy and computational efficiency perspective. For example, the most precise flow routing algorithm is of little practical use if its required processing time for an average DEM is too long.

The development of GIS based hydrologic analysis software packages is an extremely active research field and a number of products are available. Many of these applications have been released or significantly improved since the initiation of this research project and will continue to be revised in the future. Hence, the material in this section of the literature review is likely to become out of date faster than previous sections and the reader is advised to check current internet and literature sources for the most up to date information on available software applications. Nonetheless, the following sections will outline the algorithms included and resultant capabilities of the leading software for raster DEM based hydrologic analysis applications in the field.

2.11.1 ArcGIS

ArcGIS is the most widely used GIS software in the world and is developed by Environmental Systems Research Institute (ESRI) in the USA. ArcGIS provides a functionality enabling research parties to write algorithms as Dynamic Link Libraries (DLL) and scripts in Visual Basic for Applications (VBA) which can be seamlessly integrated with the core software. ESRI has supported development of two main products for hydrologic modelling within their GIS environment, namely the Arc Hydro tools and TauDEM.

Arc Hydro

Arc Hydro is a set of tools developed primarily by a research team at the Center for Research in Water Resources at the University of Austin, Texas lead by Dr David Maidment. Arc Hydro is comprehensively described in the recent ESRI press book "*Arc Hydro: GIS for Water Resources*" (Maidment 2002). Arc Hydro allows for DEM conditioning using the AGREE method of drainage enforcement (*page 43*), pit filling and the J&D algorithm (*see page 46*). Flow routing is applied using the single direction D8 algorithm (*see page 50*). Stream identification and delineation is based on user identification of Stream Area Threshold (SAT) using the constant threshold area method (*see page 67*) and raster to vector conversion of subsequent stream cells. Catchments and subcatchments are delineated based on drainage to point or line attributes which signify drainage outlets or stream reaches respectively. Arc Hydro can convert raster subcatchments to polygon representations and construct maps of upstream and downstream contributing / discharge areas.

Arc Hydro is a user-friendly group of sequential tools built into the traditional ArcGIS interface which helps to make it a powerful tool that is relatively simple to apply. However, Arc Hydro is built on the simplest algorithms for flow routing (*D8 Algorithm*) and flat area processing (*J&D Algorithm*) which are known to produce poor results in many circumstances.

TauDEM

TauDEM is also an add-on module for ArcGIS, however it has been based on utilising a multiple direction flow routing algorithm (*D∞*) and more objective approaches to identification of the SAT value. TauDEM was developed at Utah State University in Logan, Utah by Dr David Tarboton. TauDEM uses the same DEM conditioning techniques as Arc Hydro (*AGREE method, pit filling and J&D algorithm*) but applies the D∞ algorithm instead of the D8 method for flow routing. Furthermore, TauDEM allows for Strahler ordering of stream segments and the resulting calculation of bifurcation ratios and stream order statistics. This technique also allows for a more quantitative assessment of the SAT value in order to construct the most highly detailed channel network that conforms to the '*laws*' of geomorphology, namely the constant stream drops law (Broscoe 1959). This law states that the mean drop between start and end elevations of stream segments of different Strahler orders should have no clear trend. Tarboton suggests using a Student's t-test to assess the difference in means between the mean stream drop of 1st order Strahler streams and the mean stream drop of all higher order Strahler streams for a range of stream networks generated at different SAT values. The minimum SAT that yields a stream network where the t-test indicates that the means are not statistically different with a 95% confidence interval (*ie., $t \approx 2$*) should be adopted.

TauDEM has improved capabilities compared to Arc Hydro in that it can undertake Strahler ordering and can provide a more objective justification for selection of a SAT value for channel identification. TauDEM also retains the user friendly interface inherent in the ArcGIS user environment and the sequential tools are simple and relatively quick to implement. However, TauDEM does suffer from some of the particular problems associated with multiple flow direction algorithms and those problems specifically outlined for the D∞ method (*see page 56*). Furthermore, TauDEM does not improve on Arc Hydro's use of pit filling and the J&D Algorithm.

Both the Arc Hydro tools and TauDEM are freely available by download from the internet. However, in order to use either, a user must own a software licence to at least ArcGIS (*with ArcInfo licence*) as well as the *Spatial Analyst* additional software product.

2.11.2 TOPAZ

TOPAZ (*TOpographic PArameteriZation*) is a topographic analysis software application developed by Jurgen Garbrecht and Lawrence Martz at the US Department of Agriculture (USDA) and the University of Saskatchewan in Saskatoon, Saskatchewan respectively. Similarly to Arc Hydro, TOPAZ is based on the D8 method for single direction flow routing and the SAT based constant area threshold method of channel identification. However, the model uses improved methods for DEM conditioning and claims to be able to distinguish between sink-depressions and impoundment-depressions. The former of these are groups of cells lower in elevation than their neighbours and the later are caused by small bands of cells obstructing drainage from larger areas. TOPAZ treats these situations differently by filling the sink-depressions and breaching the impoundment depressions (Martz and Garbrecht 1998). As outlined previously, stream identification is achieved using a SAT approach, however, an additional parameter may be applied to prune short 1st order streams from the stream network. The user may designate a Minimum Source Channel Length (MSCL) and any 1st order stream segments that are not equal to or greater in length than this parameter will be removed from the network. The SAT and MSCL are also permitted to vary across the project. TOPAZ also allows for Strahler ordering and calculation of associated geomorphologic statistics.

The most current version of TOPAZ is 3.12 and was released in November 1999, no further development seems to have taken place since this time. The source code and manuals for TOPAZ are available free of charge upon written request. TOPAZ is written in ANSI standard FORTRAN 90 and consists of 6 programs that must be used sequentially although not all programs need to be executed for every project. Parts of the TOPAZ model have been incorporated in the Watershed Modelling System (WMS) product sold by BOSS International.

2.11.3 RiverTools

RiverTools was originally an academic research project undertaken by Scott Peckham at the University of Colorado and is now being sold as a commercial product by Rivix Pty Ltd. The model incorporates both the D8 and D∞ methods of flow routing similarly to TauDEM in ArcGIS. DEM conditioning can be applied using a number of flat cell resolution algorithms including the J&D Algorithm and a customised breaching algorithm. Streams may be identified using the constant threshold area approach and Strahler ordering is possible. Subcatchments can be delineated based on user designated outlets or intersections of streams of particular Strahler orders.

The RiverTools functionality is very similar to TauDEM in ArcGIS with minor improvements to flat and pit grid cell resolution. However, it suffers from similar flaws associated with the D8 and D∞ approaches and is only available as commercial software (*~$900 US*).

2.11.4 Tapes-G

TAPES comprises two main software groups, TAPES-C which is a contour and flow line model (*see page 16*) and TAPES-G which is designed for use with raster DEMs. The TAPES-G software was developed by Ian Moore, and development and documentation has been continued by John Gallant at Centre for Resource and Environmental Studies (CRES) and John Wilson at University of Southern California.

TAPES-G uses pit filling and the J&D algorithm to create a compatible DEM for flow routing. The software accommodates application of the D8, Rho8, FD8 and DEMON flow routing algorithms. TAPES-G is primarily able to develop flow direction grids and flow accumulation grids as a function of the flow routing algorithm but has little functionality for stream delineation, Strahler ordering or coupling with hydrologic models.

TAPES-G is written in FORTRAN 77 and C for Unix systems. It can be downloaded as source code and FORTRAN and C compilers are required on your system to compile the code. The software is non-visual and has little native GIS compatibility since no further development has occurred since August 1997.

2.11.5 Grass GIS

GRASS (Geographic Resource Analysis Support System) is a free GIS application that operates on various platforms through a graphical user interface. GRASS is based on the concept of open source programming operating under the GNU General Public License (GPL). This enables anyone to view or modify the software source code and add their own algorithms to the package. Some of the key GRASS algorithm for DEM based hydrologic analysis are:

- **r.fill.dir :** Generates a depression-less DEM and a flow direction map from a given DEM using pit filling and the J&D Algorithm.
- **r.drain :** Traces flow from an individual grid cell through the DEM using the D8 method.

- **r.water.outlet :** This algorithm delineates a catchment region from a D8 flow direction grid and a set of coordinates representing the outlet point of the catchment.
- **r.watershed :** generates a set of maps including locations of watershed basins and also the LS and S factors of the Revised Universal Soil Loss Equation (RUSLE). This function utilises the D8 flow routing and accumulation methodology and is equivalent to running r.drain and r.water.outlet for the entire DEM and multiple outlets. The r.watershed algorithm is also capable of extracting stream networks based on the SAT based approach.
- **r.terraflow :** This algorithm produces identical results to the r.watershed algorithm, however, the focus of r.terraflow is on efficient processing of massive grids. This is achieved by optimising memory management and disk-swapping. In a study by Arge et al. (2001), the algorithm was found to be able to process massive terrain grids much faster than the r.watershed algorithm. The r.terraflow algorithm processed a DEM with 11283 rows x 10862 columns (> *122 M grid cells*) in 3.5 hours where for the same DEM the r.watershed algorithm was stopped after 6 days and it was less than 1% complete at this stage. The r.terraflow algorithm is also capable of implementing the D∞ algorithm switching to D8 when the maximum cross-grading area threshold is reached.
- **r.flow :** This algorithm uses an aspect driven flow routing algorithm that traces flow as a line (*vector*) in the direction of aspect (*similarly to Lea's method, see page 54)*. This algorithm produces vector graphs of flow path mapping and does not form part of the r.watershed subcatchment delineation approach.

- **r.flowmd :** This algorithm divides flow upstream of each cell proportionally between one cardinal and one diagonal grid cell based on the distance between the intersection node and those adjacent cell centres similarly to the D∞ algorithm.

GRASS GIS is under continual development by a world-wide network of developers and is the 'flag-ship' of the Free GIS development community (www.freegis.org). It may be downloaded as executables or source code from http://grass.itc.it.

2.12 CONCLUSIONS FROM THE REVIEW

The integration of GIS systems and hydrologic models appears to be a natural progress of GIS development and the increasing availability of high-quality spatial data sets. However, many of the parameters required by hydrologic models cannot be directly read from spatial data and must be derived or generalised from the data sets using algorithms. The required algorithms are a function of the data model of the spatial information, available computational resources and ultimate end-use for the derived parameters.

A comprehensive investigation was undertaken into the most suitable DEM data model for hydrologic analysis which considered raster, TIN, contour and flow line and quadtree DEM models. It was found that raster DEMs presented the best potential for automated hydrologic analysis due to their significant advantages of ease of sampling, growing quality and availability, and their computational simplicity. A further consideration in the decision was that the commonly stated disadvantage of raster DEMs, specifically their large hard-disk and memory (*RAM*) consumption requirements are rapidly becoming less significant. The advantages of raster DEMs and the decreasing significance of the disadvantages of raster DEMs explain why the bulk of work in this field concerns raster DEMs and they will also be the focus of this research project.

DEMs may be derived from a number of sources including remote sampling by aerial photogrammetry, satellite and field survey. They may also be interpolated from other data sets include point data, TIN networks and vector contour data sets. A number of interpolation regimes are available ranging from point searching methods to surface fitting approaches. The suitability of an interpolation algorithm will be a function of the data source and computational resources.

Prior to use of a DEM in a hydrologic analysis, it is important to consider the effects of DEM errors, horizontal resolution and vertical precision. These factors have all been shown to affect the results of 'downstream processes' such as hydrologic or hydraulic simulation. In general, a higher horizontal resolution and vertical precision of a DEM will result in a more accurate calculation of topographic and hydrologic attributes, and will support generation of more realistic stream networks. However, it is important to be cognisant of the quantity and quality of actual spatial information that was used to derive the DEM. For example, a DEM interpolated from a coarser resolution spatial data set does not necessarily contain any additional information than the original data set despite the perceived increases in detail. In a comprehensive study, a user will try to assess the quality and 'fitness for purpose' of a DEM using methods such as Root Mean Square Error (RMSE) or elevation frequency distributions.

A fundamental requirement for routing flow over a DEM is that flow paths should be able to be traced from all points within the catchment of interest through downstream cells until the catchment outlet is reached. Drainage enforcement algorithms using independent vector stream GIS layers can be used to ensure global flow trends follow an observed stream network, whereas flat and pit resolution algorithms handle local flow anomalies. Many techniques are available to achieve flat and pit cell resolution, however the most common method is pit filling followed by the J&D Algorithm which iteratively assigns flow directions at flat cells towards other cells with assigned flow directions. However, this approach has been shown to produce parallel stream paths and artificially bias drainage density and associated geomorphologic calculations. More advanced methods use combinations of filling and breaching to ensure flow connectivity. The most promising approaches appear to be weighted graph techniques such as the Priority First Search (PFS) method which ensures flow paths travel through the path of least topographic resistance and form fractal stream networks in preference to parallel stream regimes.

The choice of flow routing algorithm for hydrologic DEM analysis is arguably the most important decision in such an analysis since inaccuracies in the algorithm can have a cumulative effect on 'downstream processes' such as stream network generation and subcatchment delineation. Flow routing algorithms can be categorised into single and multiple flow direction algorithms as a function of the number of downstream cells to which the algorithms can allocate flow. The most commonly applied algorithm is the D8 method which allocates flow to one of its eight neighbouring cells based on which cell represents the steepest descent path. This method is generally accepted to introduce significant errors into flow routing calculations. Single flow direction algorithms cannot represent divergence whereas multiple flow direction algorithms often over-represent divergence. Consequently, many software applications that utilise multiple flow direction algorithms recommend switching to a single flow direction algorithm after a threshold flow accumulation value has been reached (*maximum cross-grading area*). A number of multiple flow direction algorithms were presented of which the most popular is the D∞ algorithm. However, all multiple flow direction algorithms produce 'fuzzy' catchment boundaries and cannot support extraction of a connected vector stream network unless a maximum cross-grading area threshold is used.

An important drawback of all raster based flow direction algorithms (*single and multiple direction*) is that it is difficult to obtain an accurate representation of flow length since flow is transferred as a raster quantity from one cell to the next. In reality, considering water as a flowing parcel, it is impossible for a flow parcel to travel from a cell into a diagonal neighbouring cell without first flowing into a cardinal neighbouring cell, since raster DEM cells share a zero width boundary with diagonal neighbours. Vector flow routing algorithms provide a solution to this problem by representing flow as a line and modelling its entry and exit points from each raster cell and its cardinal neighbours to establish a flow path originating from the centre of the origin cell. Lea's (1992) algorithm and the DEMON method were presented as the most promising vector flow routing algorithms although inconsistencies resulting from determining flow directions by best-fit of a plane to four points can introduce anomalies into their calculated flow directions.

Stream network generation involves deriving a connected vector representation of the channel network from the DEM. Methods for achieving this based on flow accumulation grids and curvature approaches were presented. Curvature approaches can seldom be applied unless a treated contour data set is available or the DEM is topologically well behaved and vertically quantised. Flow routing based methods can utilise various parameters to identify the expected start of a channel segment. Most commonly, this is based on a Stream Area Threshold (SAT) which is constant over the project, however, variable SAT methods, slope-area methods and SAT and Minimum Source Channel Length (MSCL) approaches have been investigated. Current research does not suggest that any of these approaches provides an excellent method of channel head identification and none is statistically better than another. However, comparisons are complicated by the control data for comparison (that are usually cartographic blue line networks) which themselves have been shown to differ significantly from field observations. Stream networks also inherent artefacts and inaccuracies from the flow routing algorithm that was applied. For example, a stream network generated using a constant SAT and the D8 method may deviate from that generated by other single flow direction algorithms using the same constant SAT.

Hydrologic analysis of parameters and stream networks derived from DEMs is an integral part of GIS aided hydrologic analysis. A large number of local and global parameters can be extracted from DEMs as outlined in Section 2.9.1 (*see page 73*). Additionally, calculated stream networks can be analysed from a geomorphologic and hydrologic perspective on a local, global or drainage area basis. These analyses can be used to help ascertain rainfall response parameters and linear or non-linear lag coefficients for hydrologic models that may be applied.

Automated topographic analysis of DEMs for hydrologic modelling can only offer significant benefits if the large amount of information derived during the analysis can be successfully transitioned through to the hydrologic modelling software. This process is termed 'coupling' of the GIS and the hydrologic model. There are four main types of coupling, integration of the GIS within the hydrologic model, integration of the hydrologic model within the GIS, and loose and tight coupling of independent implementations of the GIS and the hydrologic model. Whilst the first two full integration approaches offer the most seamless interaction of the technologies, it can be impractical from a development perspective since the two products must now be developed as one. More importantly, integration of GIS and hydrologic modelling faces more fundamental problems as a result of their differing representations of space, time and randomness. Contrary to these approaches, loose and tight coupling allow the potential for the products to evolve independently provided the links between them are maintained to ensure compatibility. From a computational design perspective, loose and tight coupling represent differing approaches to data storage and management. Tight coupling allows both applications to operate on the same files and databases whereas loose coupling provides links for seamless data transfer between the native data formats of the software applications. However, the distinction between these two coupling methodologies can be invisible to the user and the increased practicality of loose coupling is often preferred. Furthermore, modern object-orientated programming techniques such as the Component Object Model (COM) mean that complex features such as bi-directional feedback loops can also be implemented with loose coupling.

A comprehensive analysis of the available raster DEM based hydrologic analysis software packages was undertaken. The key features of these software products were identified and the specific algorithms they have adopted were compared. The most popular software, Arc Hydro within the Arc GIS framework utilises the simplest algorithms, that is, the D8 method with J&D flat and pit cell resolution and a constant SAT based representation of stream networks. More advanced applications such as TauDEM, RiverTools and GRASS GIS were all investigated. All available software packages except TauDEM used the D8 method to route flow between raster cells, however some also offer the D∞ algorithm for multiple direction flow routing. TAPES-G accommodates flow routing by a number of other algorithms including the FD8 and DEMON algorithms, however, little other functionality is offered by this product. The J&D flat and pit resolution algorithm was implemented by all software packages except TOPAZ despite its known problems of parallel stream generation and associated hydrologic parameter bias. RiverTools and TOPAZ incorporated breaching algorithms to assist in flat and pit cell resolution. No software product was found to employ weighted graph based approaches to flat and pit cell resolution such as the Priority First Search (PFS) approach (*see page 46*). Stream network delineation was achieved by the Stream Area Threshold (SAT) method in all software products, however, TauDEM offers a geomorphological analysis tool for more objective determination of the SAT value. TOPAZ also offers a further parameter designed to prune 1st order streams from the network by setting of a Minimum Source Channel Length (MSCL). RiverTools and TauDEM were the only products that allowed for Strahler ordering and associated analysis of vector stream networks. The ArcGIS (*Arc Hydro and TauDEM*) and GRASS GIS software environments offer macro languages to aid in coupling between GIS and hydrologic models, however programming in these languages is often too difficult for many software users. No software packages were found to provide any inherent links with, or existing macro scripts for common Australian hydrologic models.

This review has provided an in-depth analysis of the GIS structure and data models applicable to automated hydrologic analysis as well as the theoretical aspects of the leading algorithms available for these processes. Furthermore, a review of the practical application of these algorithms in leading software packages has been described. This research project is aimed to assess the suitability of available software applications and their associated algorithms for GIS based hydrologic analysis. Following this, new algorithms or revised implementation of existing algorithms will be proposed and incorporated in a new software application designed to produce more hydrologically realistic results than available techniques.

3 APPLICATION DESIGN

3.1 INTRODUCTION

The goal of this research project is to investigate the adequacy of current approaches to automated hydrologic analysis of DEMs for lumped subcatchment modelling. If these techniques are found to be inadequate, the research objective is to undertake design and development of a new software application that improves upon existing techniques from the perspective of:

- Accuracy of internal algorithms and end results;
- Usability, compatibility and affordability of the software; and,
- Integration with existing Australian and international hydrologic models.

It is apparent from the literature review that neither the algorithms available for automated hydrologic analysis of DEMs, nor the current software implementations of these algorithms are entirely effective. This is evidenced by the lack of adoption of these techniques in Australia and around the world. The reasons for this are wide ranging and include:

- Oversimplified and error-prone geo-spatial algorithms within conventional GIS software for calculation of terrain attributes (*such as the D8 method*);

- Where more advanced algorithms have been implemented in software, it is usually non-user-friendly text based software that does not provide coupling with hydrologic models;
- Poor compatibility between international commercial GIS software and highly country-specific 'industry standard' hydrologic modelling software packages;
- The expense associated with many conventional GIS packages / add-on modules (*particularly true for developing countries*).

As such, a new software design that aims to meet the aforementioned objectives has been developed. The basic outline of internal algorithms and software design is presented in the following sections, and a comprehensive description of the completed application is presented in Chapter 4.

3.2 DESIGN METHODOLOGY

It is important to note that algorithm and software design is a balancing act between speed, complexity and usability. The most hydrologically realistic algorithms may be excessively complex algorithms that require very high computational run times. They may also require expert users to apply them effectively and are, as a result, outside the comprehension of the average user. This may mean that the use of software incorporating such algorithms is not practical for the average user with the average computer. Consequently, the benefits of the more accurate algorithms are forfeited by a lack of software use. Thus, the advantages of more complex algorithms must always be viewed in the context of their impacts (*usually negative*) on speed and usability.

Furthermore, the end use of the derived results should always be considered. For example, as outlined in Section 2.7.3 (*page 59*), Wolock and McCabe (1995) observed slight differences between single and multiple flow direction algorithms when comparing TOPMODEL model efficiency and simulated flow paths. However, these differences disappeared when the model was calibrated by adjustment of subsurface hydraulic parameters. These result were obtained using a distributed model (*modelling of individual cells*). Hence, the advantages of multiple flow direction algorithms for hydrologic analysis of DEMs designed for lumped hydrologic modelling are likely to inconsequential compared to the disadvantages of fuzzy subcatchment boundaries and exaggerated flow divergence.

The Arc Hydro tools reviewed in Section 2.11.1 (*page 85*) were the most user-friendly software implementation of available hydrologic analysis algorithms, but were found to be overly simplistic. This research project aims to maintain this simplicity of use while incorporating more advanced algorithms and providing better coupling with Australian and international hydrologic models. To achieve this objective, the proposed software design incorporates the capabilities and associated algorithms outlined in the following sections.

3.3 DEM IMPORTING, INTERPOLATION AND SAMPLING

For the reasons outlined in Section 2.3.3 (*page 22*), the software should be based on raster DEMs as opposed to TIN, contour and flow line, or quadtree DEM data models. It needs to be able to take advantage of the increasing amount of sampled DEMs that are becoming available today, including SRTM and AUSLIG DEM data. Furthermore, it should accommodate re-sampling of excessively detailed DEMs and conversion of TIN DEMs. In this way, the software will be able to be applied in any region where a DEM exists.

However, the software should also be applicable in areas where no DEM exists or where available DEMs are not of a size, horizontal resolution or vertical precision that adequately define the hydrologic processes being modelled. That is, the software should incorporate algorithms to interpolate a DEM from other spatial data sets.

As documented in Section 2.4.1 (*page 29*), DEM interpolation from contours holds the most promise for automated hydrologic analysis of DEMs. This is due to a number of factors including:

- Digital contour data sets are widely available due to their use as a cartographic layer on many topographic maps. Contour lines that are printed but no longer available in digital format can also be easily digitised or scanned to vector format by specialised computer hardware and software.

- As documented by Wise (2000), vector contour lines exhibit extra information than simply a string of points of common elevation. Interpolation algorithms can be designed to take advantage of this extra information.
- Contour alignments have often been manually adjusted to better represent the terrain surface. As a result of these manual adjustments, much less hydrologic conditioning will be required after interpolation of the DEM. Consequently, the DEM will be more hydrologically suited than one developed from other geo-spatial data sets.
- Traditionally, catchment and subcatchment delineation for hydrologic modelling has been achieved by manual tracing over topographic maps exhibiting contour lines. Hence, automated hydrologic processing of DEMs interpolated from contours provides the most potential for synergy with industry standard techniques since both processes are based on the same data sets.

The software should be able to utilise a 2D watercourse alignment GIS layer (*blue lines on topographic maps*) to improve the resulting interpolated surface since these data sets are often available in the same regions where contour lines are available. This capability will improve the model's ability to represent valley and runoff regions. Since watercourse alignment information does not contain elevation data, it will need to be utilised in conjunction with the contour data set in order to ensure drainage enforcement.

The interpolation algorithm should be designed to take full advantage of the information available in contour data sets whilst allowing maximum user flexibility and quick processing time. The interpolation regimes outlined in Section 2.4.1 (*page 29*) were all investigated in the context of the objectives of the project, contour data set properties, ease of algorithm application and the computational demands of each algorithm, to determine the interpolation algorithm design. As a result, a profile based algorithm was selected as the interpolation algorithm based on its speed, relative simplicity and suitability of use with contour data.

However, important modifications are proposed to overcome the limitations of traditional profile based approaches. Most profile algorithms simply apply a raster searching algorithm in the eight directions defined by cardinal and diagonal grid cells. These algorithms suffer from the potential for diagonal search paths to miss rasterised contour lines and are also unlikely to produce a search line that correctly identifies the normal slope line between two contour intervals. These algorithms are also biased in ridge areas by many search rays finding contours of the same elevation. These problems are described in greater detail in Section 4.4.2 (*page 128*), however the key modifications proposed to the profile algorithm to improve the resulting interpolated surface are:

- Use a vector profile algorithm, that is, search for assigned cells along a linear path rather than a diagonal or cardinal set of grid cells. This allows for a better representation of distance to assigned cells which will create greater accuracy in the cross-section linear interpolation phase.

- Allow the user to specify the number of profiles they wish to use in the interpolation regime. For example, if the user has the available computational resources, they could use 50 or 100 search rays (*as opposed to 8 in traditional profile algorithms*) which would greatly improve the algorithm's accuracy.
- Overcome the tendency of profile algorithms to underestimate elevation in ridge areas by flat cross-section discounting in the weighting of interpolated cross-section elevations. Furthermore, a manual tool to assist users to better represent ridge lines if they are unsatisfied with the interpolated surface should be incorporated into the software.

The drainage enforcement and DEM interpolation algorithms are to be designed to ensure that a user can quickly develop a DEM that is well suited to hydrologic analysis. More complex interpolation algorithms such as kriging and polynomial fitting were not selected as interpolation regimes due to their computational demands, expertise required for users to correctly apply these algorithms and the fact that these algorithms are not necessarily constrained by the closest data points. However, the software should allow users to import DEMs that were interpolated in other software products which may utilise other interpolation algorithms.

3.4 DEM CONDITIONING

The drainage enforcement and interpolation algorithms outlined in the previous section should ensure that for internally interpolated DEMs, only a small amount of DEM conditioning will be required. However, the software must be sufficiently robust to ensure that imported remotely sampled DEMs with high noise levels and DEMs derived in urban areas with many closed depressions, can be effectively conditioned in a hydrologically realistic manner.

The combined pit filling and J&D algorithm approach that has been adopted in the majority of available software products has been deemed to be inadequate due to its parallel flow path problems and failure to breach large closed depressions (*see Section 2.6.2, page 44*).

A trait of the profile based DEM interpolation algorithm will be that hill-crests are flattened off at their uppermost contour line unless additional spatial data is provided at the hill-crest. This is because the final contour is a loop contour and all profile rays initiated from a cell within this loop will find the same contour elevation and be assigned an equal elevation. The software should include an algorithm to treat these anomalies and ensure that hill-crests are given a realistic shape where the centroid of the loop contour is assigned the highest elevation.

As a result of the investigation documented in Section 2.6.2 (*page 44*), the PFS algorithm was selected as the most promising flat and pit cell resolution technique. However a number of important modifications were proposed including:

- Processing of flat and pit cells in order from lowest to highest elevation to improve the identification of major flow paths.

- Introduction of a user settable minimum downslope gradient criteria to avoid potential identification of minor undulations in topography as algorithm outlets and also to overcome potential problems with vertical precision rounding.
- Introduction of two more parameters, namely 'algorithm break size' and 'no-data treatment' to ensure quick processing times (*see Section 4.5.2, page 137*).

The DEM conditioning algorithms have been selected to ensure the optimum solutions on sampled and interpolated DEMs. Furthermore, they have been designed to be suitable for application to noisy and urban DEMs.

3.5 FLOW ROUTING

A wide range of flow routing algorithms for automated hydrologic analysis of DEMs were investigated, as documented in Section 2.7 (*page 49*). These included single and multiple direction raster flow algorithms as well as single direction vector flow algorithms. Despite its advantages of simplicity and speed, the D8 algorithm was deemed too inaccurate to be applied in the software.

Multiple direction flow routing algorithms were not selected to be utilised in the software because of their over representation of divergence and the fact that boundary cells may be associated with more than one subcatchment which will cause difficulty in derivation of clear subcatchment boundaries. Furthermore, most proponents of multiple direction flow algorithms suggest switching to the D8 method after a set threshold (*maximum cross-grading area*) to avoid excessive divergence. Thus, even with the adoption of a multiple flow direction algorithm, in areas of major flow paths where stream networks will be derived, the most inaccurate algorithm (D8) will end up being applied.

It was concluded that a vector flow routing algorithm such as Lea's (1992) method holds the most promise for application in the software due to the following attributes:

- Allows flow to follow any angle from 0 - 360° overcoming the disadvantage of the D8 method where flow is restricted to eight directions.
- Models flow as a vector quantity, hence, obtaining a realistic value for flow path length measurements.
- Allows for accurate flow path calculations without exaggerating flow divergence or producing 'fuzzy' subcatchment boundaries.

However, as outlined in Section 2.7.3 (*page 59*), the DEMON and Lea's (1992) algorithm suffer from the inaccuracies associated with fitting a best-fit plane to 4 points which are themselves averages of the surrounding cell values. Furthermore, as Tarboton (1997) pointed out, perhaps only the neighbouring cells of lower elevation are of relevance to flow routing calculations. As such, a similar algorithm to Lea's (1992) algorithm was proposed for use in the software, however, flow angle will be calculated only by analysis of the downslope cardinal neighbouring cells as opposed to all neighbouring cells. This will ensure that flow can only travel towards cells of lower elevation and will also increase the speed of the algorithm.

3.5.1 Flow Routing in Urban Areas

Urban features such as gutters and drainage swales are usually not represented in a DEM due to the small size of these features in comparison to the DEM resolution, or the fact that these features may have been constructed after the sampling of the DEM. However, urban features strongly affect flow in these areas. These issues have effectively precluded the successful application of automated hydrologic analysis of DEMs in urban areas. The proposed software should incorporate algorithms to overcome this problem.

This should be done in a manner that does not necessarily involve direct modifications to DEM cell elevations, as users may wish to turn on or off these urban features to assess their hydrologic impact. Such urban features should include gutters and drainage channels that act as supplementary controls to the DEM. That is, flow paths will follow DEM derived flow paths until intersecting with an urban feature which will then dictate the flow path, overriding the DEM until the flow path is no longer in proximity to the urban feature.

3.6 STREAM NETWORK GENERATION

Derivation of a connected vector stream network will be an important facet of the software which enables calculation of associated geo-statistics and provides functionality for automated subcatchment delineation.

As described in Section 2.8.1 (*page 66*), the first stage of stream network generation is identification of channel heads. A number of methods to identify channel heads were considered including Stream Area Threshold (SAT), Minimum Source Channel Length (MSCL), slope-area thresholds and curvature approaches. Research has indicated that no one method produces significantly better results than the others. Curvature methods, although attractive in principle, are difficult to apply in automated DEM analysis and may also fail to generate a connected stream network with appropriate hydrologic connectivity.

It is proposed to implement both the SAT and SAT / MSCL approaches to channel initiation to ensure that the user is provided with flexibility. More importantly, it is necessary for the software to incorporate means for assessment of the appropriate SAT value for the user to adopt. TauDEM is the only software product that encompasses this ability at the moment and its features are quite limited in this area. The proposed software should include a clear graphical approach to identification of the appropriate SAT and MSCL value.

After the generation of channel heads is complete, the flow routing algorithm is used to create the connected vector stream network. All available software packages use the D8 method as the basis for stream network generation. This includes applications that utilise multiple direction flow algorithms since these usually have a maximum cross-grading area threshold to ensure divergence doesn't occur in stream channels. As such, these applications are also utilising the D8 algorithm in stream areas. Since the proposed software is using a more advanced flow routing algorithm than the D8 algorithm, the calculated stream network should benefit from this improved accuracy. This should have a follow-on effect in more accurate stream network geo-statistics and better delineation of subcatchment boundaries that are based on stream networks.

3.7 HYDROLOGIC ANALYSIS

One of the key disadvantages of offering automated hydrologic analysis in conventional GIS software applications is that these programs often do not have specialised analysis tools to investigate the hydrologic properties of the subcatchments. This can inhibit the creation of knowledge necessary to better assign parameters in any ‘downstream’ hydrologic or hydraulic modelling package that may be applied. The proposed software will be specialised towards hydrologic applications and should focus on these types of analyses.

In addition to calculation of important hydrologic properties such as those listed in Section 2.9.1 (*page 73*), a number of graphic and non-graphical analysis frameworks should be introduced to help assess the hydrologic properties of subcatchments. The software has significant potential to excel in this area due to the flow path length capabilities provided by the proposed flow routing algorithm. This algorithm makes a lot of analyses possible that could not be undertaken using the D8 algorithm.

Strahler / Horton analysis should be incorporated into the software including calculation of bifurcation ratios for individual subcatchments at a range of SAT values. RiverTools and TauDEM are the only products offering Strahler ordering of a vector stream network and both of these products use the D8 method within channel segments. As a result, Strahler analysis cannot presently be undertaken on stream networks generated by more advanced flow routing algorithms. The proposed software will overcome this problem.

A range of other charts and associated parameters should be incorporated into the software to take advantage of the capabilities of the flow routing algorithm. An example of such charts are plots outlining the overland, in-stream and total flow length frequency distributions for all cells within an individual subcatchment. An example of an associated parameter would be O_{50} – overland flow distance before 50% of subcatchment cells have encountered a stream segment. The range of available charting options is shown in Section 4.11 (*page 162*).

3.8 COUPLING WITH 3RD PARTY SOFTWARE

As described in Section 2.10 (*page 78*), many of the potential benefits of automated hydrologic analysis of DEMs are lost if this information cannot be easily and seamlessly transitioned to a ‘downstream’ hydrologic or hydraulic computer model. The fact that most Australian lumped hydrologic models are setup manually is an unfortunate indication that the potential contribution of GIS aided automated hydrologic analysis has gone mostly unrealised in Australia.

Consequently, it is important to ensure that seamless coupling exists between the proposed software and a full range of Australian and international hydrologic models. In Australia these models should include RAFTS-XP, WBNM, RORB, URBS and DRAINS at a minimum. This coupling should be independent of the GIS system to ensure that the two systems can develop independently whilst coupling link maintenance will ensure future compatibility. This coupling methodology will also overcome the problems associated with differing representations of space, time and randomness between GIS and hydrologic models.

3.9 CONCLUSION

Development of a software product to meet the objectives outlined in the preceding sections was initiated in January 2002 and is on-going, 15 successive versions of the software have now been released and the software has a wide profile of users (*see Section 6.1, page 193*). The capabilities of the subsequent software, named CatchmentSIM and an overview of the internal algorithms are outlined in Chapter 4.

4 APPLICATION OVERVIEW

This chapter provide an in-depth explanation of the algorithms which were developed and embodied within the CatchmentSIM application. The algorithms are in described in the logical order that they would typically be called on during a CatchmentSIM project. This chapter serves to outline the capabilities of these algorithms and provide an introductory examination of their benefits as compared to other methods. Comparative analysis of the more complex algorithms is documented in Chapter 5.

4.1 INTRODUCTION

To aid in the understanding of this chapter and to gain a perspective of the computational nature of the algorithms, the reader is encouraged to install the CatchmentSIM software and complete the tutorial shown in **Appendix A** using the sample data supplied on the Data CD included as **Appendix E** (*or available from the project website* http://www.uow.edu.au/~cjr03). The tutorial outlines the operation of CatchmentSIM from a more instructional perspective using many screen images of the various operations, whereas this chapter is written from an algorithm design perspective.

As described in Chapter 3, CatchmentSIM has been designed for the purpose of calculating parameters for hydrologic and hydraulic models using more advanced techniques than other products currently being utilised in the field. Specifically, CatchmentSIM can be used to delineate a catchment, break it up into numerous subcatchments and determine their topographic and hydrologic attributes. This information can then be analysed to provide insight into the rainfall response of various subcatchments and resultant assignment of hydrologic modelling parameters. Following this, the derived subcatchments and their attributes may be directly coupled with any 3rd party hydrologic model. This is achieved by a flexible macro language with specifically developed macro scripts, which enable automatic development of input files (*text or binary*) for other models.

4.2 SETTING UP A NEW PROJECT

The first stage in development of a CatchmentSIM project is to set the project boundaries. These boundaries should be large enough to accommodate the catchment of interest but should not be excessively large and include a large amount of redundant topography. The project boundaries are used to trim all data that is imported into the project. This allows the use of large GIS data sets as input data for a project. For example, after a user sets appropriate project boundaries which are large enough to contain the catchment under analysis, they may then assign a very large GIS database as the project source data, such as a database containing digital contours and watercourses for an entire Council Local Government Area (LGA). CatchmentSIM will only import and store the digital terrain information that is within the project boundaries. Contour or stream lines that cross project boundaries are clipped at their point of intersection. Consequently, the same source database may be used for many projects without manipulating the data with the parent GIS application. In fact, it is not necessary to own any commercial GIS software, merely, to have access to the appropriate database in an accepted format. CatchmentSIM provides all the tools required for basic data manipulation including addition / deletion of contours and watercourse data.

4.3 IMPORTING GIS DATA

The next stage in building a CatchmentSIM project is to import suitable GIS data from a number of supported data formats. If the DEM is to be interpolated from contour and watercourse data then this data may be imported as Mid / Mif files (*MapInfo Data Exchange Format*) or ArcGIS ShapeFilies. If the DEM is being imported such as a sampled DEM, or a DEM interpolated in another application, then the DEM may be imported in the common ARC-INFO ASCII GRID format.

4.4 DEVELOPMENT OF A DIGITAL ELEVATION MODEL

As outlined in Section 2.3.3 (*page 22*), raster DEMs have shown the most promise for automated hydrologic analysis. The DEM may be interpolated from 3D contour data and 2D watercourse data, or it can be imported from external applications. Additionally, the DEM may be sampled from an external raster or TIN DEM.

4.4.1 DEM Boundaries and Resolution

In the case of interpolating a DEM within the project or sampling an external DEM, the first step is to define the boundaries and resolution of the DEM. The rectangle defining the external boundary of the DEM can be set by the user to be any size equal to or smaller than the selected project boundaries, and may have any number or rows and columns. The software will generate a warning if it determines that the DEM characteristics are outside of the user's computational resources. CatchmentSIM does not require DEMs to have square cells and can accommodate rectangular grid cells. However, an option is available to ensure that the DEM has square cells. If this option is selected then the number of DEM columns will be automatically calculated after the user enters the number of DEM rows to ensure a square cell DEM is developed.

In order to maximise the precision of the analysis within the available computational resources, the DEM boundaries should be chosen carefully to ensure the smallest possible DEM that contains the entire catchment is created. The total number of cells should be maintained in a reasonable range. For example, a project with 1 million cells (*eg., 1000 rows * 1000 columns*) requires about 10 -12 MB of hard disk space (*for all project files*) and the most computationally intensive algorithm requires about 3 minutes to process (*on a Pentium 2.4 GHz*). The computational demands of the software in terms of storage space and processing time will both increase with the number of cells in the DEM. However, the accuracy of any subsequent hydrologic analysis can be related to the grid cell resolution (Goonetilleke and Jenkins 1996). As such, the DEM boundaries and number of rows / columns should be chosen carefully as a balance between desired accuracy and computational resources.

However, if watercourse data is planned to be incorporated into the model (*recommended if available*) it is important to set the project boundaries so that the next contour line intersection point along the main stream downstream of the desired catchment outlet is included within the project boundaries. This ensures that the drainage enforcement algorithm is able to be applied to the entire reach of the main stream within the catchment.

The DEM precision can also be set in CatchmentSIM. This refers to the number of significant figures to which elevation values are recorded. The user may choose between single precision (*7-8 significant digits*) and double precision (*15-16 significant digits*). The use of double precision will double the hard-disk and memory requirements for the DEM file. Double precision storage of DEM values may only be necessary in regions with large vertical ranges or values that are recorded in small increments such as feet. For example, if single precision is being used and elevation values reach 10,000 then only 2-3 decimal places may be recorded which may be insufficient to represent very gradual slopes if the horizontal resolution is high.

4.4.2 DEM Interpolation

The minimum data requirement for interpolation of a DEM is 3D contour data. The accuracy and fitness for the purpose of such a DEM will be primarily a function of the level of contour definition of the imported data and required spatial resolution of the model. However, the DEM quality may be greatly improved by using a vector watercourse layer in conjunction with the interpolation algorithm. These data layers are utilised by the DEM interpolation algorithm in a number of sequential steps, namely:

- Vector to raster conversion of 3D contour lines;
- Incorporation of watercourse GIS layers (*optional*);
- Interpolation of raster DEM;
- Implementation of interpolation aids (*optional*); and,
- Stream burning (*optional*).

Rasterisation of Contour Data

To incorporate the vector contour data into the DEM it is necessary to convert the contours to a raster format. The basic principle behind vector to raster conversion is to assign cells underlying the line (*vector component*) the same attribute (*elevation*) as the line. However, research has shown that applying the elevation attribute to every cell underlying the line does not produce a good raster representation of the vector data. This can be seen in **Figure 4-1** which illustrates the raster representation of a sample line.

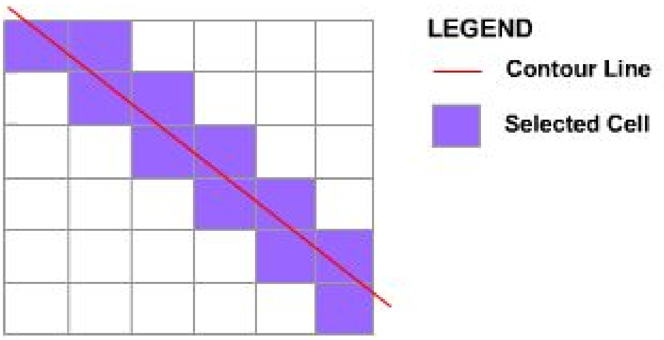


Figure 4-1 : Vector to Raster Conversion of All Underlying Cells

It can be seen that assignment of all underlying cells has converted a zero-width line into a two cell wide terrain segment of constant elevation. A cross-section generated perpendicular to this contour line would yield a flat section at each imported contour line. To overcome this problem it is generally accepted that only selected cells underlying the line segment should have the line attribute applied. CatchmentSIM uses a well accepted and documented decision structure to determine which cells will form the raster representation of the line, which is governed by the following rule.

Should the vector component exit a cell and traverse two of the cell's neighbouring eight cells then only the cell containing the longest portion of the line will be applied the vector attribute.

The example illustrated in **Figure 4-1** has been reproduced in **Figure 4-2** but with the improved vector to raster conversion methodology. It can be seen that the new algorithm is a better solution than that portrayed in **Figure 4-1**. This is especially relevant in areas of closely spaced contours.

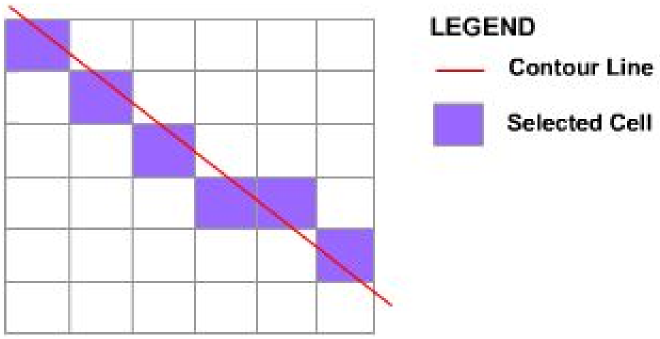


Figure 4-2 : Selective Vector to Raster Conversion

All contour information that has been imported into the project is rasterised into the DEM prior to incorporation of watercourse data layers.

Incorporation of Watercourse Data

GIS layers of watercourse data typically do not have any 3D attributes. That is, elevations of watercourse polyline vertices are not provided. Furthermore, drainage direction is not usually provided. Hence, this data must be used in conjunction with the rasterised contour data to be incorporated into the analysis.

CatchmentSIM interprets watercourse information as paths of DEM cells along which cell elevations should smoothly and consistently decrease (*in a downstream direction*) between intersected contour cells. The algorithm processes each tributary in a downstream direction, applying the watercourse algorithm between intersected contour lines until a DEM boundary or previously interpolated watercourse cell is found. Tributaries are processed in order of decreasing starting elevation (*as a function of local contours*) to ensure that main stream interpolation takes priority over interpolation of minor tributaries. This process is illustrated in **Figure 4-3**.

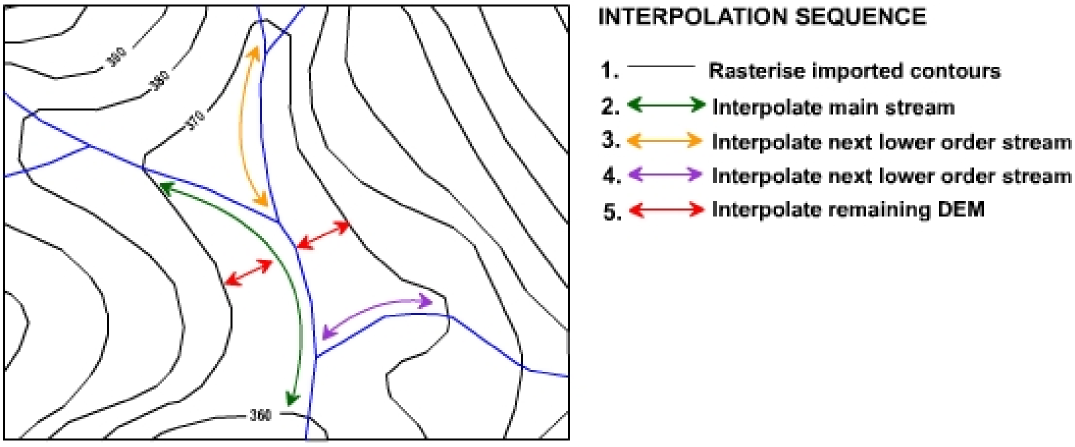


Figure 4-3 : Stream Processing Sequencing

The process is complicated due to the fractal network nature of watercourse alignments and the tendency of this data to be provided as thousands of partial watercourse segments that exist between junctions of two or more segments. As stated previously, these line segments have no 3D attributes and often the individual segments are not large enough to intersect the necessary two contour lines to allow linear interpolation. CatchmentSIM processes the watercourse network to identify single polylines that travel from each upstream tributary down to the sink associated with that tributary. This algorithm can process any stream network (*with no limit on the number of segments in a junction*) provided connecting stream segments end / start at the same coordinate pair or within a user designated distance tolerance. ArcGIS also has the capability to form directional drainage networks from watercourse GIS layers but it requires the user to identify the sinks associated with all tributaries. This is not a problem if the network is fully connected and thus only has one sink. However, in many catchments, particularly in Australia, streams are often discontinuous with ephemeral streams and channel termination common. This can cause manual identification of all sinks within a catchment to be a tedious process. Consequently, the CatchmentSIM algorithm was designed to be fully automated and automatically identifies all sinks. The algorithm only requires each tributary line segment to cross at least two non-equal contours in order to assign drainage direction.

The net effect of the watercourse integration algorithm is a more realistic and hydrologically suitable DEM that preserves a known watercourse network. In most cases, after the application of the watercourse integration algorithm, calculated flow paths will follow those of the imported GIS watercourse layer as shown in **Figure 4-4**.

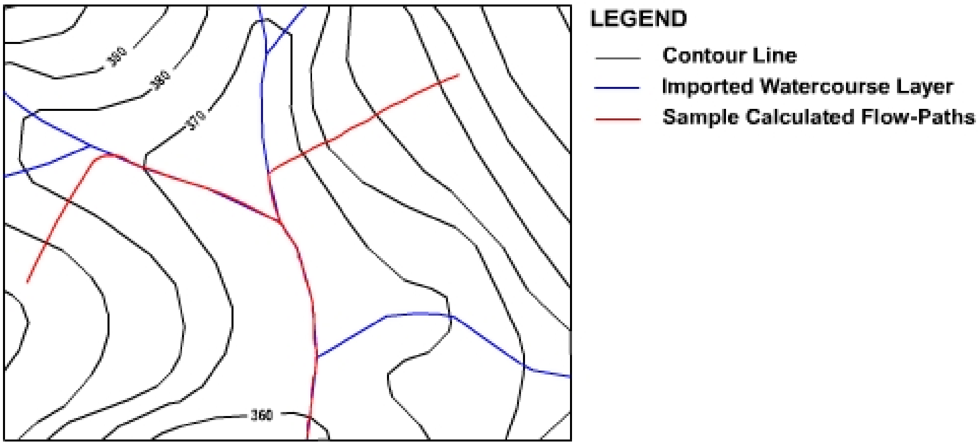


Figure 4-4 : Adherence of Calculated Flow Paths to Stream Network

It is important to note that the watercourse integration algorithm does not force flow paths to follow the imported watercourse layer, rather it acts as a guide to the DEM interpolation mechanism. To ensure 100% flow path mapping adherence to the watercourse alignments, a stream burning algorithm can be implemented (*see page 132*).

Interpolation Aids

The degree to which the DEM is closely representative of the real terrain is a function of the quantity and quality of the source data from which the DEM was interpolated. Limited source data may impact on the interpolation algorithm's ability to represent hydrologically important topographic features such as watershed divides and convergent flow paths. The best solution for any problematic regions is to import additional contour and watercourse data, however, this is often not available or economical. For this reason, CatchmentSIM incorporates a range of tools that can be applied in areas of concern to augment and improve the automated interpolation process.

Head's Up Digitising of Additional Contour Lines

In addition to importing contours from GIS or survey applications, they can also be manually digitised within CatchmentSIM. This may be valuable in areas where a large area of terrain falls predominantly between the contour intervals. An example of this is shown in **Figure 4-5**, where an additional contour has been manually digitised to remove a resulting uncertainty in the interpolation surface. As shown, CatchmentSIM does not require contour lines to be continuous and any amount of additional data can be digitised at the user's discretion.

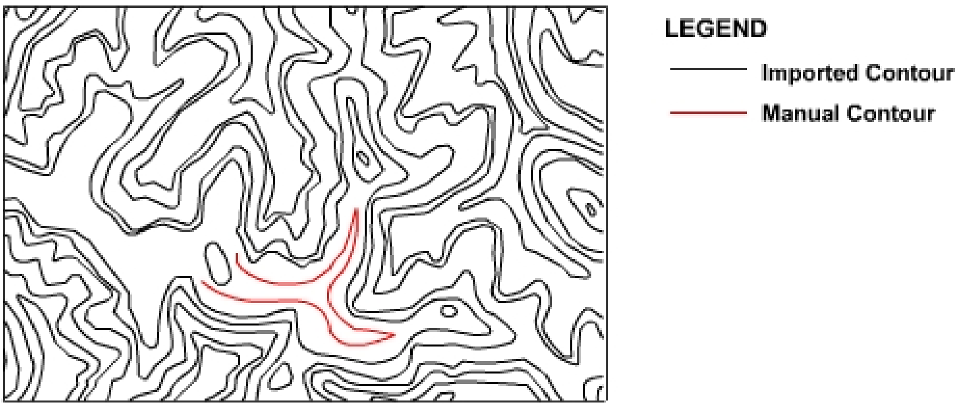


Figure 4-5 : HUD Digitising of Contour Lines

Head's Up Digitising of Additional Watercourses

Similarly to contour lines, additional watercourse alignments can be manually digitised within CatchmentSIM. These lines will be incorporated into the DEM in an identical fashion to the watercourse GIS layer. The manually digitised watercourse alignments can be 'snapped' to the existing watercourse network to ensure the junction resolution algorithm can operate successfully. An example application of Head's Up Digitising (HUD) of watercourses is shown in **Figure 4-6**.

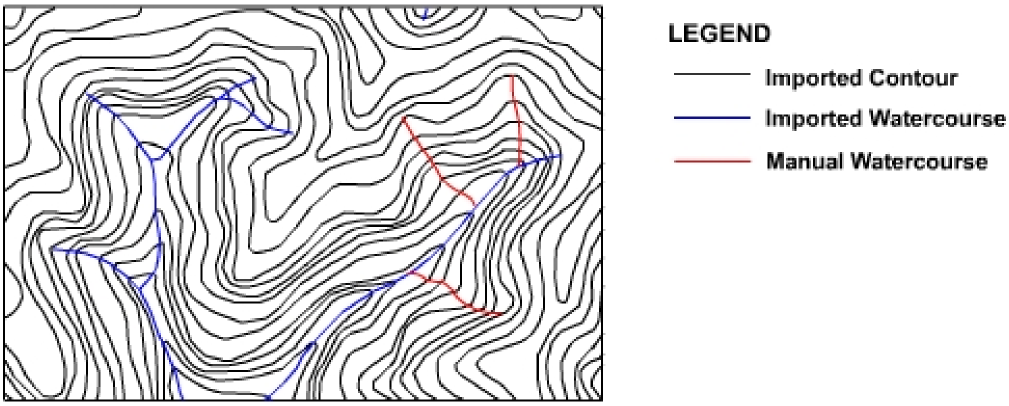


Figure 4-6 : HUD Digitising of Streams

Interpolation Training Lines (ITLs)

CatchmentSIM allows Head's Up Digitising (HUD) of Interpolation Training Lines (ITL) to improve the accuracy of the interpolation mechanism along ridges and other watershed divides. ITLs are usually unnecessary, however, they may be useful in some regions of low contour definition, for example, the terrain shown in **Figure 4-7**. ITLs are incorporated into the pre-interpolation DEM in a similar manner to watercourse alignments. That is, along these lines elevation values are interpolated linearly between intersected contour lines prior to interpolation of the remaining DEM.

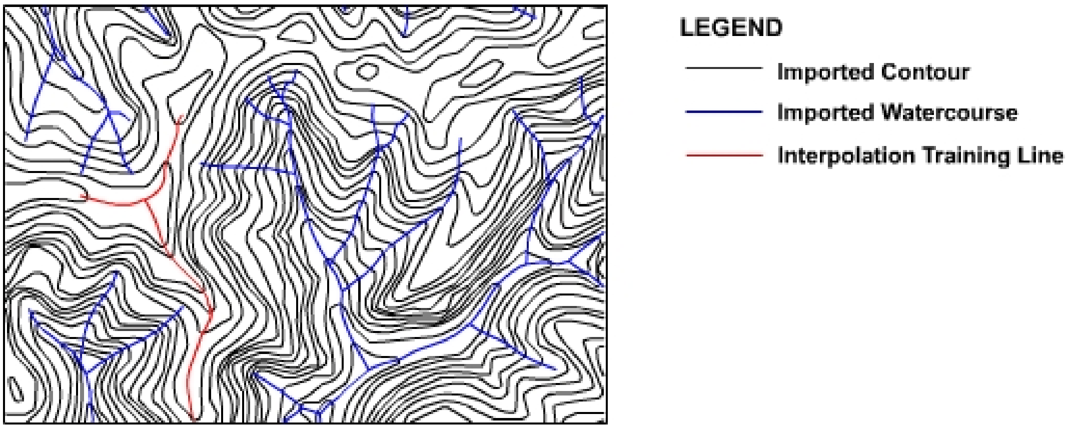


Figure 4-7 : HUD Digitising of ITLs

By importing a good coverage of 3D contour lines and 2D watercourse lines, and placement of some strategic interpolation aids, users are able to quickly create the basis for interpolation of a hydrologically suited DEM.

DEM Interpolation Algorithm

The DEM interpolation phase refers to the calculation and assignment of elevations for all DEM cells that remain unassigned following the source data rasterisation and watercourse interpolation phases.

CatchmentSIM uses an interpolation algorithm based on a distance weighted average of a series of linear interpolations along a user-designated number of cross-sections taken through each cell. For example, the interpolation regime shown in **Figure 4-8** exhibits a 16 ray interpolation sequence. The 180 degree arc is divided into 8 increments and interpolation rays are initiated at the appropriate angles. All rays are paired with a mirror ray which travels in the opposite direction (ie., + 180 degrees).

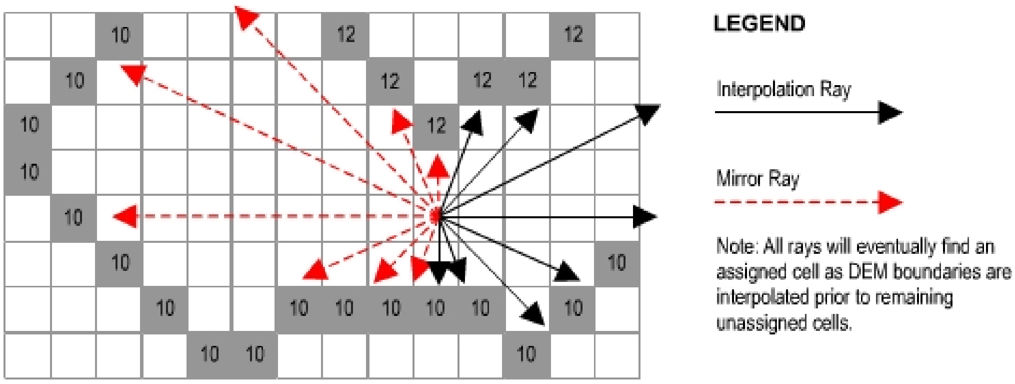


Figure 4-8 : Interpolation of Digital Elevation Model

Once an interpolation ray and its corresponding mirror ray both intersect cells with assigned elevations, linear interpolation is applied to determine the cell elevation for that particular interpolation and mirror ray combination. The final value for the cell is based on a weighted average of all the cross-section interpolations. The individual cross-section weights are based on the inverse of the distance between the located assigned cells for the cross-section. During the algorithm development process it was found that flat cross-sections should be discounted (*smaller weights*) since they were over-flattening the topography in certain situations. An example of this can be seen in **Figure 4-9**.

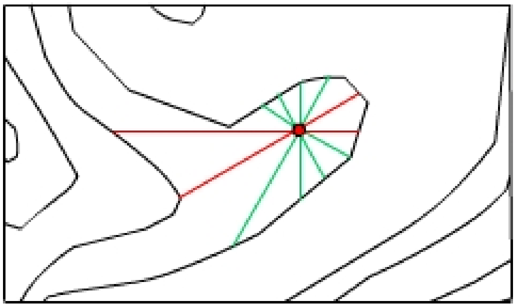


Figure 4-9 : Flat Cross-Section Discounting Scenario

As illustrated in **Figure 4-9**, the non-flat cross-sections shown in red have the longest lengths and would consequently be given the smallest weights. However, due to the apparent ridge line evidenced by the contours, these cross-sections are more representative of the actual terrain and should be given more dominant weights than the surrounding flat cross-sections. These situations are accommodated by giving all flat cross-sections a discounting factor (*FB*) in their weight calculation as shown in **Equation 4-1**.

$$W_N = \left(\frac{1}{D_N * FB} \right) \qquad \textbf{(Equation 4-1)}$$

In **Equation 4-1**, W_N is individual cross-section weighting, D_N is the distance between the assigned DEM cells and FB is the flat cross-section discounting factor which is assigned the value of 1 except in the case of flat cross-sections where it is set at 10. This value was determined by empirical evaluation and visual analysis of the generated surface.

The final elevation of the cell is calculated as shown in **Equation 4-2** where W_T is the sum of all individual weights and Z_N is the linearly interpolated elevation for each individual cross-section.

$$Elevation = \sum_{n=1}^{\#rays}\left(\frac{W_n}{W_T} * Z_n\right) \qquad \textbf{(Equation 4-2)}$$

CatchmentSIM allows the user to designate the number of interpolation rays (*and mirror rays*) that are used to interpolate the cell elevation. Increasing the number of rays will increase the accuracy of the interpolated surface as well as the computational demands of the algorithm. **Figure 4-10** illustrates the advantages of increasing the resolution of the DEM interpolation algorithm.

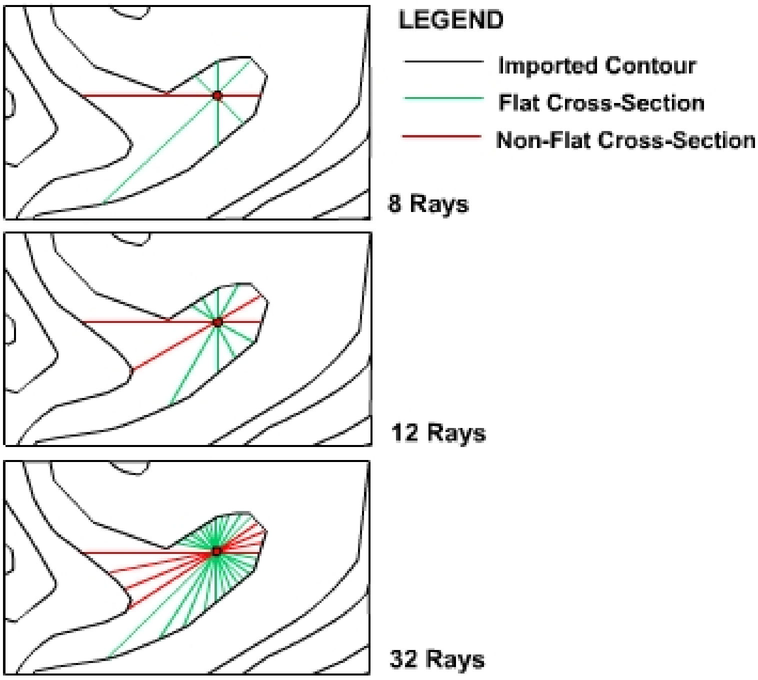


Figure 4-10 : Increasing Resolution of DEM Interpolation

It can be seen in **Figure 4-10** that the 32 ray interpolation algorithm has four non-flat cross-sections which will realistically represent the expected ridge line in the area. Ultimately, the best solution is reached when a cross-section alignment is found that is normal to the intersected contour lines, thus is approximately equal to local aspect. The 8 ray algorithm almost missed finding a non-flat cross-section, which would have resulted in a calculated elevation equal to the lower contour value. If there is no linear segment that can be found to construct a non-flat cross-section then an ITL should be used to correctly represent the ridge line. It is recommended that users adopt the maximum number of rays that their time requirements can accommodate. The relationship between number of rays and algorithm run time is directly linear (*ie., twice as many rays will take twice as long*). Algorithm run time will also increase with total grid cells and sparsity of contour and watercourse data, since the search rays will need to travel further to find assigned cells.

Stream Burning

The watercourse interpolation algorithm outlined in Section 4.4.2 (*page 119*) does not force flow paths to follow the imported watercourse alignments, rather it simply ensures that cells along the watercourse alignments are linearly interpolated between intersected contour lines prior to interpolation of any surrounding cells. In most cases, this will ensure the watercourse alignments are preserved in the drainage network. However, in some areas of low relief or complex stream paths, it may be found that calculated flow paths depart from imported watercourse alignments. If this presents a problem then stream burning can be implemented. This algorithm will artificially lower cells that underlie watercourse alignments to ensure they are represented as flow paths in the calculated stream network. However, it may slightly bias slope calculations that are generated later in the analysis.

Figure 4-11 illustrates the effect of application of the stream burning algorithm. It can be seen that the pre-stream burning flow path (*green line*) deviates slightly from the imported watercourse's path (*blue line*), whereas application of the stream burning algorithm has 'snapped' the flow path to the observed watercourse.

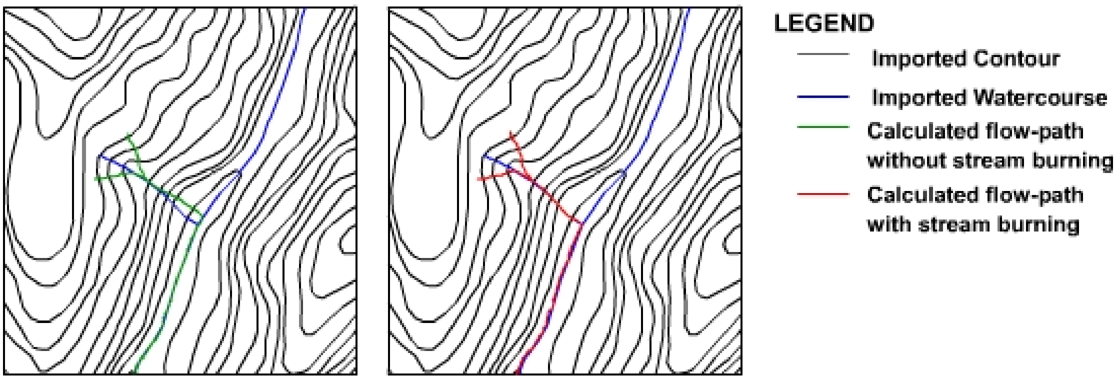


Figure 4-11 : Effect of 'Stream Burning' on Flow paths

Prior to using the stream burning algorithm it is important to determine if it is necessary, as its use can slightly bias calculated values for some of the topographic indices that are generated at a later stage, such as average vectored slope. Furthermore, in **Figure 4-11** it could be argued that the pre-stream burning flow path is a better interpretation of the source contours (*ie., steeper descent*) compared to the imported watercourse alignment.

4.5 HYDROLOGIC CONDITIONING OF DEM

Following interpolation of the DEM, or importing of the DEM from an external application, flat and pit cells must be treated to ensure flow connectivity as outlined in Section 2.6.2 (*page 44*). Flat or pit cells will cause the flow routing algorithm to fail, hence these cells and all cells that flow into them will not be accumulated into the subcatchment that they should realistically drain to. Consequently, the subcatchment delineation will exhibit holes, which will adversely affect the calculation of subcatchment areas and geo-statistics. Imported DEMs may also exhibit pit or flat cells for a variety of reasons depending on the source of the raster data but most will be found in areas where the topographic relief is small compared with the vertical definition of the sampling technique.

CatchmentSIM includes two algorithms for removal of flat and pit cells in a DEM. The first of these is a filling algorithm which raises the elevation of flat and pit cells in an iterative manner until flow processing is possible. The second algorithm for removal of flat and pit cells is an advanced breaching algorithm based on Priority First Search (PFS) weighted graph methodology.

In the case of internally interpolated DEMs it is recommended that the filling algorithm is initially applied to remove the bulk of the flat and pit cells and treat the flattened hill crests that tend to result from the DEM interpolation algorithm. Following this, the PFS algorithm may be applied to remove the remainder of the flat and pit cells.

Where a DEM has been imported from an external application, the PFS algorithm may be applied without prior application of the filling algorithm, particularly if the flat and pit cells are in valley areas or situated along expected watercourse alignments.

4.5.1 Filling Algorithm

CatchmentSIM's filling algorithm works by first raising all pit cells to the elevation of their lowest neighbouring cell and then raising the elevation of flat cells by a set increment in order to be able to derive a downslope flow direction.

This algorithm is specifically designed to treat drainage anomalies resulting from the flattening of hill crests within the DEM where contour definition has not been provided at the crest of a hill. This occurs because all rays of the interpolation algorithm will find the same contour value, as illustrated in **Figure 4-12**.

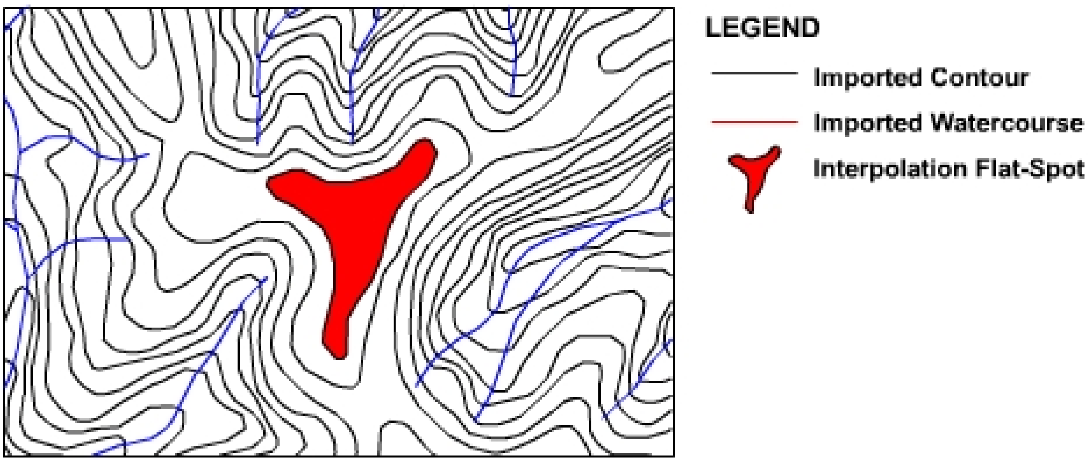


Figure 4-12 : Interpolation Flat-Spots

In these situations the iterative process implemented by the filling algorithm ensures that cell elevations in large flat areas are raised from the outside in, creating a rounded hill crest that realistically distributes flow down all sides, with the highest elevation cell located at the hill crest centroid. An animation illustrating the iterative nature of this algorithm can be found on the Data CD included as **Appendix E**.

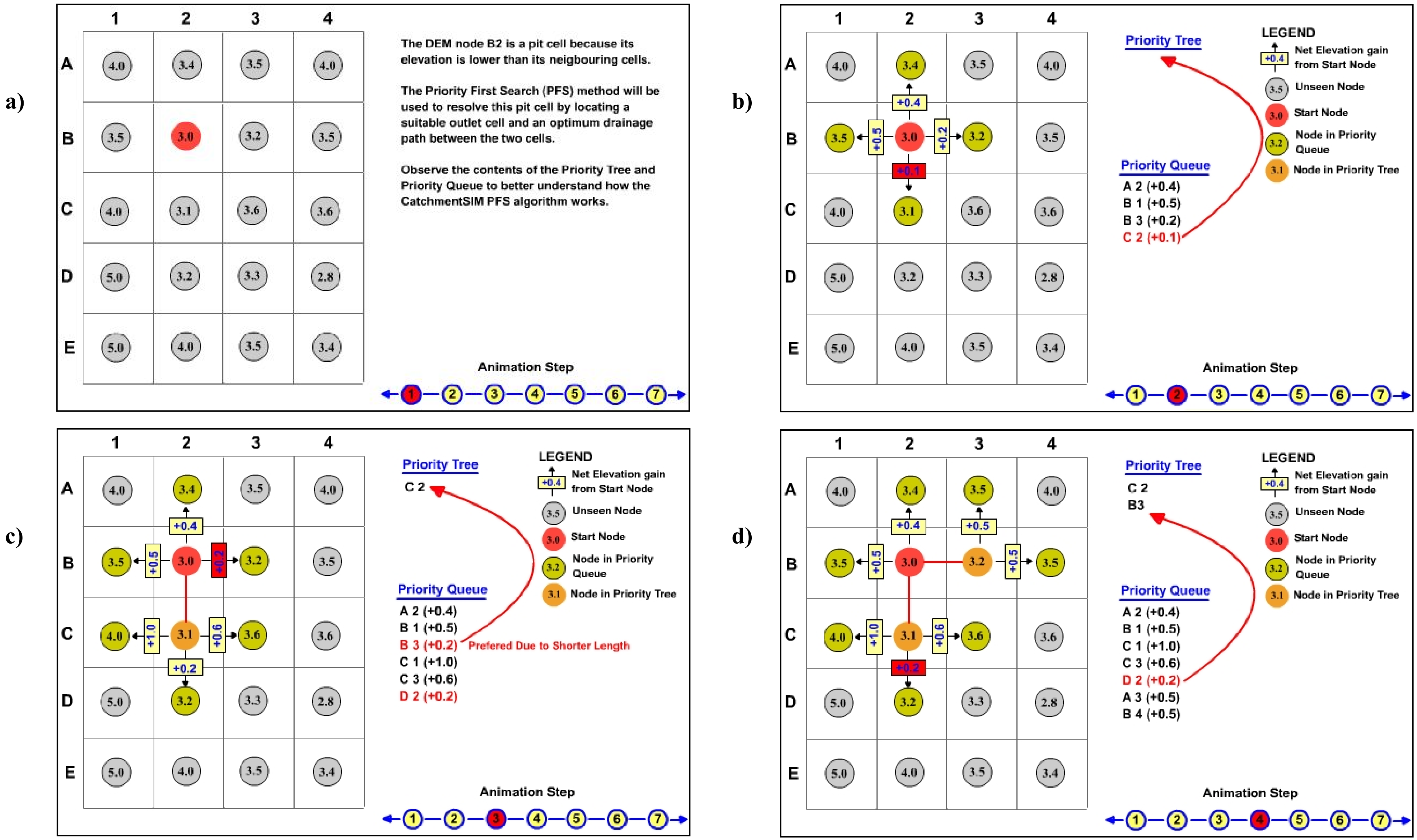
CatchmentSIM's filling algorithm is good at treating drainage anomalies formed in DEMs interpolated internally or by other ray based approaches. However, for imported remotely-sampled DEMs or stubborn flat or pit cell arrangements that are unable to be resolved by the filling algorithm, an advanced Priority First Search (PFS) weighted graphed based breaching algorithm has been included in CatchmentSIM.

4.5.2 Priority First Search (PFS) Algorithm

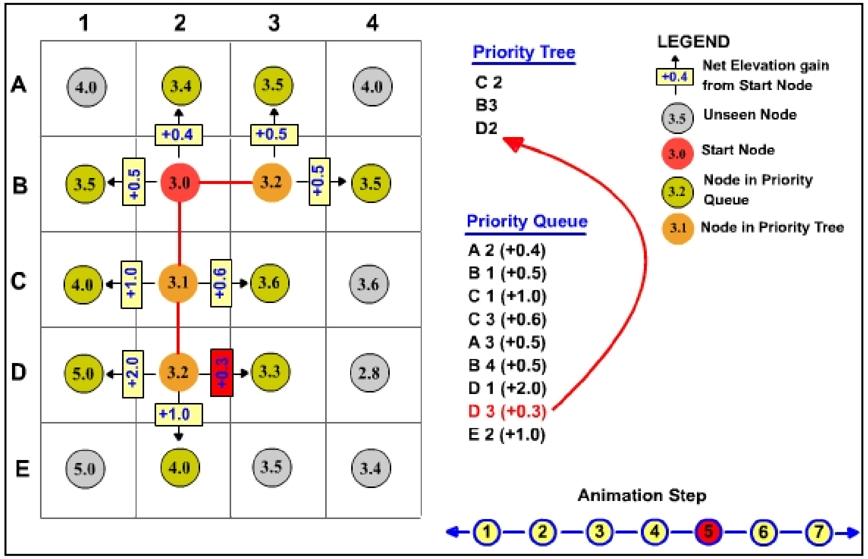
The Priority First Search (PFS) algorithm implemented within CatchmentSIM is a breaching algorithm designed to solve complex arrangements of flat and pit cells in a DEM. The algorithm can resolve any flat or pit cell within a DEM provided a cell with a lower elevation exists somewhere within the DEM. For each flat or pit cell, the PFS algorithm searches for a nearby cell with lower elevation (*outlet cell*) and an optimum drainage path between the two cells. After finding the outlet cell and optimum drainage path, the PFS algorithm will lower the elevation of all cells along the optimum drainage path to create a downslope drainage path of consistent gradient between the original flat or pit cell and the outlet cell.

The method used to implement this technique is based on well-documented weighted graph methodology (Sedgewick, Robert 1988) and has shown promise in hydrologic applications (Jones, Richard 2002). The algorithm records DEM cells or 'nodes' in two sets, the priority tree and the priority queue. As a result, all cells in the DEM are in one of three states, on the priority tree, on the priority queue or as yet unseen by the algorithm. Initially, all non-diagonal cells adjacent to the target flat or pit cell are added to the priority queue. In turn, the nodes in the priority queue are examined with reference to a priority function and the most suitable node in the priority queue is added to the priority tree and removed from the priority queue. Adjacent cells to the new node (*recently added to the priority tree*) are then added to the priority queue which now consists of the remaining nodes from the previous iteration and these new nodes. The algorithm continues until a terminating condition is met, which is triggered when a node in the priority queue satisfies the terminating criteria. In CatchmentSIM, the terminating criteria requires the node to have a lower elevation than the starting node and for the resultant downslope gradient between the two points (*along the optimum drainage path*) to exceed a user designated minimum gradient threshold.

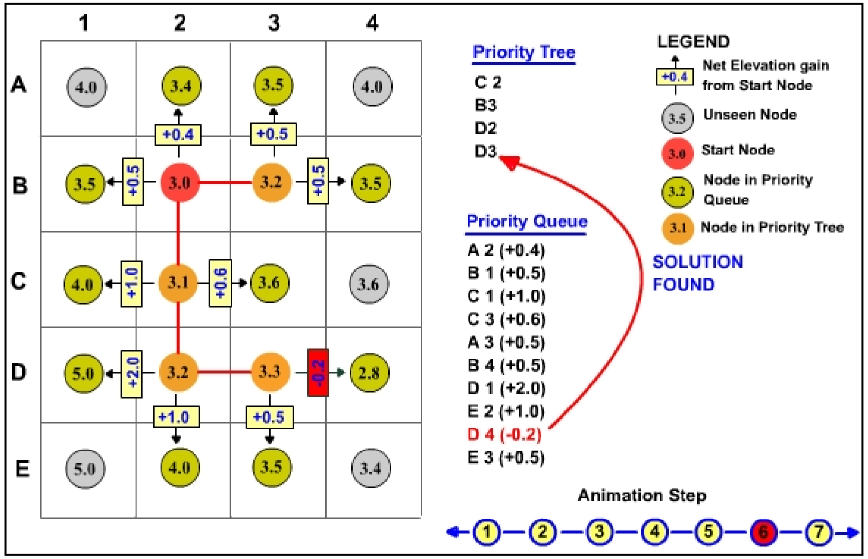
The priority function used to assess nodes in the priority queue has two criteria. Firstly, it searches for the node representing the smallest net elevation gain from the starting node. If more than one node has an equal net elevation gain then the node representing the shortest path from the starting node (*along the optimum drainage path*) is selected. This methodology is explained further in the example presented in **Figure 4-13**.


a)
The DEM node B2 is a pit cell because its elevation is lower than its neigbouring cells.
The Priority First Search (PFS) method will be used to resolve this pit cell by locating a suitable outlet cell and an optimum drainage path between the two cells.
Observe the contents of the Priority Tree and Priority Queue to better understand how the CatchmentSIM PFS algorithm works.
Animation Step
b)
Priority Tree
Priority Queue
A 2 (+0.4)
B 1 (+0.5)
B 3 (+0.2)
C 2 (+0.1)
LEGEND
Net Elevation gain from Start Node
Unseen Node
Start Node
Node in Priority Queue
Node in Priority Tree
Animation Step
c)
Priority Tree
C 2
Priority Queue
A 2 (+0.4)
B 1 (+0.5)
B 3 (+0.2)
Prefered Due to Shorter Length
C 1 (+1.0)
C 3 (+0.6)
D 2 (+0.2)
LEGEND
Net Elevation gain from Start Node
Unseen Node
Start Node
Node in Priority Queue
Node in Priority Tree
Animation Step
d)
Priority Tree
C 2
B3
Priority Queue
A 2 (+0.4)
B 1 (+0.5)
C 1 (+1.0)
C 3 (+0.6)
D 2 (+0.2)
A 3 (+0.5)
B 4 (+0.5)
LEGEND
Net Elevation gain from Start Node
Unseen Node
Start Node
Node in Priority Queue
Node in Priority Tree
Animation Step

e)



f)



g)

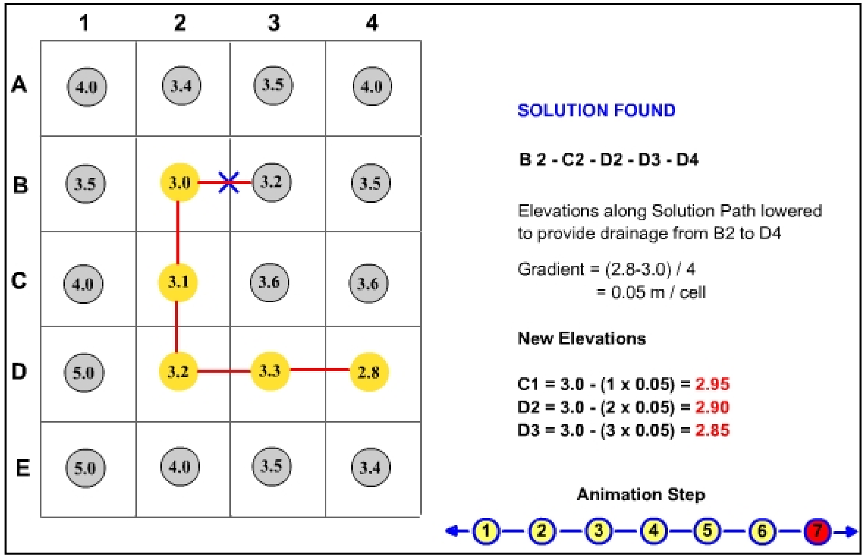


Figure 4-13 : Priority First Search Algorithm Methodology

One of the important capabilities of the PFS algorithm is that once a node is entered in the priority queue it is not removed until the algorithm is finished or it is transferred to the priority tree. This means that the priority tree can grow in any direction and will always find the optimum drainage path. A real-world example of the CatchmentSIM PFS algorithm presented in the form of an animation can be found on the Data CD included as **Appendix E**.

The optimum drainage path found by the algorithm in the animation depicted on the Data CD may not seem to be representative of the contours. However, it represents the shortest path through the lowest pass over the subtle DEM elevation variations.

The PFS algorithm can be either applied to an individual flat or pit cell by the user or to all flat or pit cells remaining in the DEM. If the later is applied then the flat and pit cells are processed by the PFS algorithm in order of increasing elevation. This improves the drainage network in flatter terrain and reduces the necessity for multiple applications of the PFS algorithm.

There are a number of options that a user can set in CatchmentSIM to dictate the properties of the PFS Algorithm, these are :

- **Minimum Gradient –** The minimum gradient that must be found to exist along the optimum drainage path for the algorithm to accept the outlet cell. This parameter is designed to ensure that significant drainage paths are identified and that gradients are not so low as to produce flat cells when DEM cell elevations are rounded to the precision of the DEM (*single or double, see page 117*).

- **No-data Behaviour –** This parameter dictates how the algorithm will behave if it encounters cells which are on the boundaries of the DEM or have not yet been assigned an elevation value. The algorithm can either terminate leaving the original flat or pit cell with its initial elevation, or continue to search ignoring the no-data or boundary cell.
- **PFS Break Size –** This parameter is used to monitor the size of the priority queue and the algorithm will terminate if the priority queue reaches this size. This is particularly important if the no-data behaviour parameter is set to ignore no-data or boundary cells. In these cases, the algorithm may search the entire DEM before realising that no cell meets the terminating criteria and moving onto the next flat or pit cell. This can slow the algorithm down to an impractical extent. To avoid this slow-down and enable the algorithm to terminate prematurely, the PFS break size parameter may be used. This parameter should be set large enough to ensure genuine solutions paths are found but small enough to restrict unwanted algorithm slow-down.

The PFS algorithm has several important advantages over other common methods. Firstly, it is robust and will always find a solution provided a cell satisfying the terminating conditions exists. Secondly, it does not distinguish between flat and pit cells resulting in a consistent approach to both types of drainage anomalies. Thirdly, it tends to create channel networks and flow distributions that are more representative of reality than competing models as outlined in Section 2.6.2 (*page 46*).

4.6 FLOW ROUTING

Following the interpolation and hydrologic conditioning of the DEM, CatchmentSIM applies a flow routing algorithm to delineate subcatchment boundaries, determine the subcatchment network relationship and calculate geophysical subcatchment properties. The flow routing algorithm forms the basis of all these processes and is of vital importance to the quality of any GIS based hydrologic investigation. As outlined in Section 3.5 (*page 108*), a modified version of Lea's (1992) method was designed for implementation in CatchmentSIM. The flow routing algorithm was modified to overcome the disadvantages of approximating flow direction by fitting a rigid plane through 4 points as outlined in **Figure 2-23** (*page 62*). This was achieved by changing the basis for flow direction calculation from approximating a plane between the average elevations of the grid cell corners (*which are themselves an average of their surrounding 4 grid cells*) to a method that only uses 3 elevation values. The resultant algorithm is quicker and will never result in flow paths that flow towards or cross into a cell of higher elevation unlike Lea's (1992) original algorithm.

The modified version of Lea's (1992) algorithm calculates a downslope flow angle for each cell that can be anywhere in the range of 0-360 degrees. The flow direction angle is determined as the resultant flow vector from the combination of the steepest non-diagonal cell flow vector and the next steepest adjacent non-diagonal vector as outlined in **Figure 4-14**.

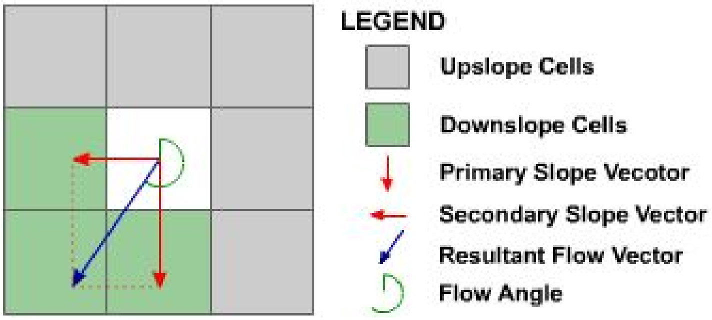


Figure 4-14 : Calculation of Flow Direction

Flow from each cell is then routed through all downslope cells until a subcatchment outlet (*or DEM boundary*) is reached. The algorithm treats the flow path as a line and records the entry and exit points of the flow path through all cells. The mechanism behind the flow path mapping algorithm is illustrated in the **Figure 4-15**.

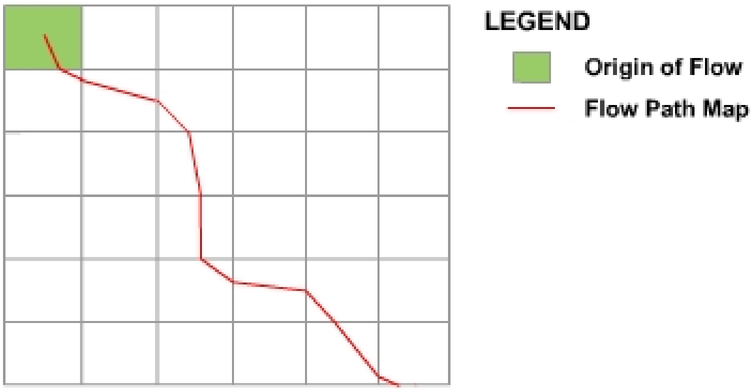


Figure 4-15 : Vector Flow Path

As shown above, the described algorithm considers flow as a vector quantity flowing through a raster DEM. This technique has distinct advantages over more common approaches which consider flow as a raster quantity. In particular, it allows a greater representation of flow direction over hill-slopes and has greater sensitivity to flow divergence or convergence. For example, **Figure 4-16** depicts parts of the CatchmentSIM flow paths mapped for 9 neighbouring cells.

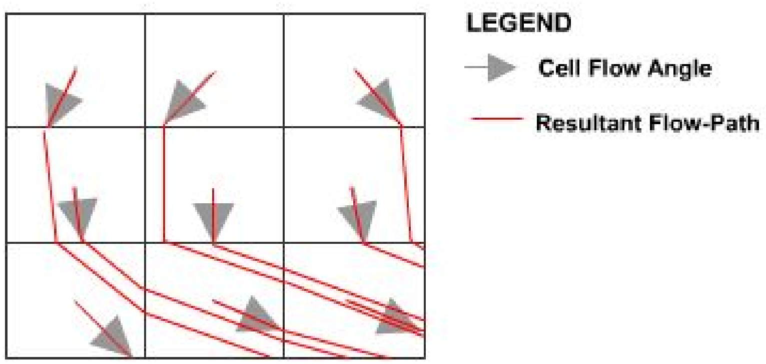


Figure 4-16 : Path Mapping Capabilities of CatchmentSIM

The distribution of flow paths can be seen in the lower right cell in **Figure 4-16** where flow paths from upstream cells are distributed between both of this cell's downslope cells, based on where the flow paths entered the cell. This cannot be accommodated in raster based flow routing techniques and allows for a more accurate representation of flow distribution, and calculated drainage-path length / slope statistics. CatchmentSIM's flow routing algorithm is analysed in more detail in Section 5.2 (*page 172*).

4.7 STREAM NETWORK ANALYSIS

CatchmentSIM allows for the generation of stream networks which are used to define relationships between subcatchments and to determine hydrological measures such as drainage density, average flow length and stream / surface slopes. Stream networks also form the basis for the automatic catchment break-up algorithms incorporated within CatchmentSIM.

CatchmentSIM can calculate vector stream networks with Horton / Strahler ordering based on channel head identification and the aforementioned vector flow routing algorithm.

4.7.1 Development of Stream Network

Channel heads can be identified in CatchmentSIM utilising a number of options as outlined in Section 2.8.1 (*page 66*). These include Stream Area Threshold (SAT) or combination of SAT with Minimum Source Channel Length (MSCL). CatchmentSIM also allows for quantitative assessment of the minimum SAT value that can be adopted whilst preserving the geomorphologic properties of dendritic stream networks.

Once channel heads have been identified, flow is mapped from each of these cells and intersections are recorded. Following this, Horton / Strahler ordering is calculated in accordance with the methodology outlined by Strahler (1957) and illustrated in **Figure 2-25** (*page 77*). The end result is a set of connected vector polylines with Horton / Strahler orders calculated for each line segment. This can be displayed in CatchmentSIM with differing colours and line styles for each stream order and analysed with a variety of charts and derived hydrologic parameters. A sample of stream order colouring can be seen in **Figure 4-18** (*page 152*).

A more detailed analysis of the Horton / Strahler stream networks produced by CatchmentSIM is given in Section 5.3 (*page 175*).

Quantitative Assessment of SAT Value

CatchmentSIM has the capability to assess the geomorphologic properties of a stream network and check to ensure it is consistent with observed stream laws as defined by Broscoe (1959), Horton (1945) and Strahler (1957). If the stream network does not conform to these laws then the stream network may not have been generated at an appropriate SAT. CatchmentSIM provides analysis tools to determine the minimum SAT that can be utilised to generate a geomorphologically suitable stream network. This is an important step because the stream network may be the basis for subcatchment break-up and hydrologic analysis. More information on this tool is given in Section 5.3.1 (*page 175*).

4.8 AUTOMATED CATCHMENT BREAK-UP

Subcatchments can be automatically delineated by CatchmentSIM on the basis of either user definition or automated assignment of subcatchment outlet cells. The subcatchments are then mapped by applying the flow routing algorithm to every cell in the DEM and assigning each cell as an attribute of the subcatchment outlet they first flow through. The program also calculates distance to subcatchment outlet and flow accumulation values at this time, and stores them in the hydrologic database.

As outlined previously, subcatchments are defined by their outlet cells. There are a number of techniques to set the outlet cells for the subcatchments including:

- Direct input of outlet cell(s) row and column numbers into a dialog box;
- Individual selection of cell(s) by clicking on the screen;
- Importing subcatchment outlets from a GIS database; and,
- Drawing an outlet line which is then automatically rasterised to derive the outlet cell(s).

CatchmentSIM also includes two algorithms designed to automatically break-up a catchment into its major subcatchments by identification of significant points of lateral inflow. The first of these algorithms requires the user to set a target number of subcatchments and then the catchment is automatically divided into this many subcatchments, based on the largest jumps in the flow accumulation matrix. The second algorithm works by identifying all subcatchments formed by intersections of stream segments in the vector stream network of particular Horton / Strahler orders. These algorithms can be used to reduce the subjectivity of subcatchment break-up and greatly increase the speed of the process. The second algorithm is probably the most objective approach because it neither requires the user to designate the subcatchment outlet locations nor the actual number of subcatchments. Furthermore, it could be expected that subcatchments of a similar Horton / Strahler order would have similar hydrologic properties.

These two subcatchment break-up algorithms are described in the following sections.

4.8.1 Flow Accumulation Jump Analysis

When using the flow accumulation jump algorithm, the user simply designates a target number of subcatchments and the algorithm will automatically break up the catchment into the correct number of subcatchments. The algorithm works based on finding the largest jumps in the flow accumulation grid values between cells in streams and their downstream neighbour which indicates lateral inflow of a significant tributary. **Figure 4-17** illustrates the subcatchment break-up achieved by the automated subcatchment break-up algorithm using 3 different target subcatchment values.

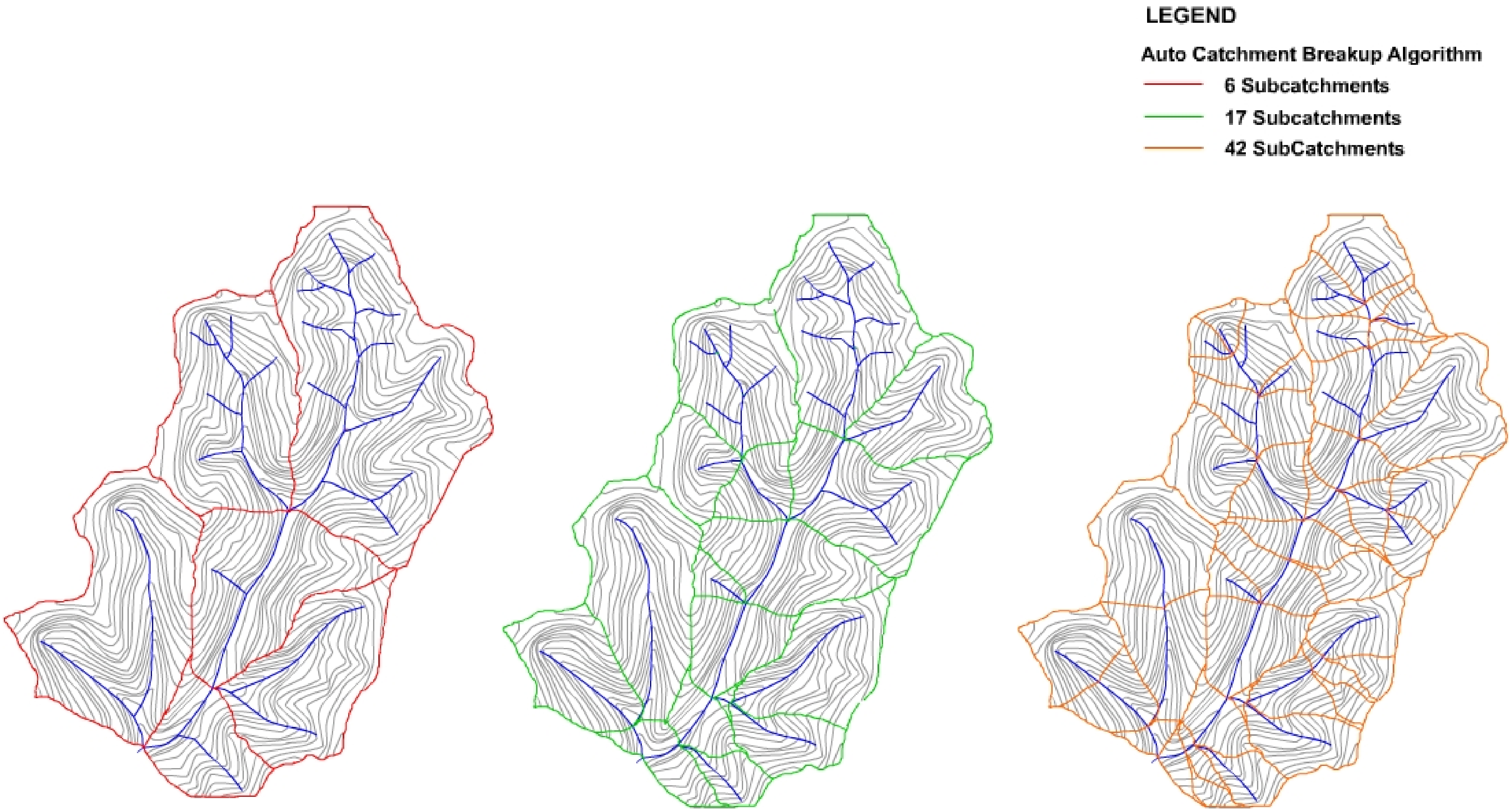


Figure 4-17 : Flow Accumulation Jump Break-up Algorithm

4.8.2 Horton / Strahler Subcatchment Break-up

The Horton / Strahler based catchment break-up algorithm requires the user to first generate a vector stream network by selection of an appropriate SAT value. This can be based on quantitative analysis of SAT derived networks as outlined in Section 4.7.1 (*page 146*) or by generation of a stream network that closely matches an observed stream layer. At this point, a user can select what order subcatchments to delineate. For example, if a user selects 3rd order subcatchments then subcatchment outlets will be placed upstream and downstream of all intersections in the stream network where two or more of the tributaries have an order greater than or equal to 3. As a result, the total number of subcatchments as well as the precise location of subcatchment outlets will be a function of the hydrologic properties of the vector stream network. An example of the subcatchment break-up achieved on a sample catchment when delineating subcatchments of differing Horton / Strahler orders in shown in **Figure 4-18**.

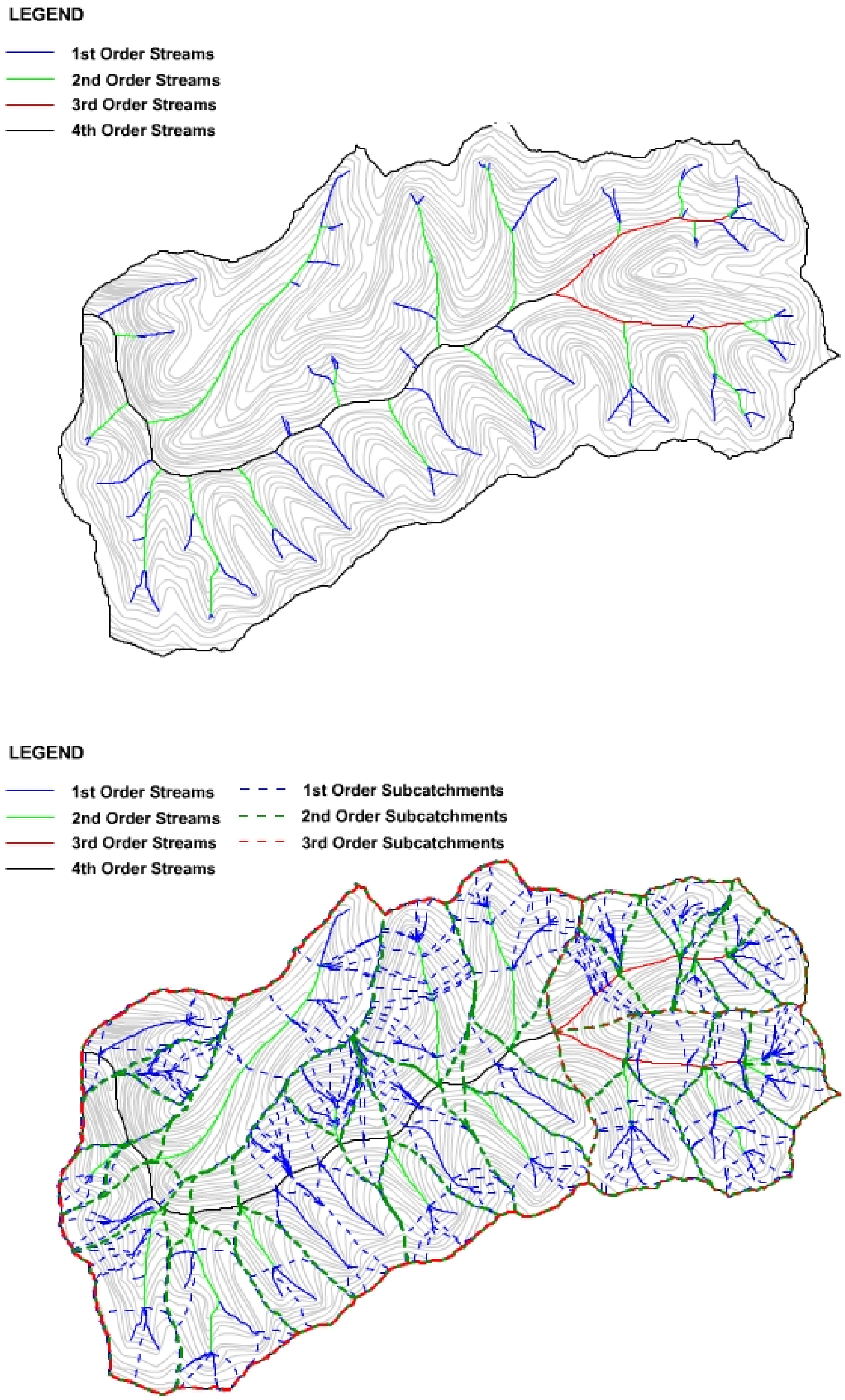


Figure 4-18 : Horton Catchment Break-up Algorithm

Utilising the Horton / Strahler ordering approach to catchment break-up provides the foundations for a standardised approach to lumped hydrologic modelling and reduces the guesswork involved in designation of the number of subcatchments and location of the subcatchment outlet points. For example, if a standard SAT is adopted for a specific geographic region then any lumped hydrologic modelling applied in this area could use Horton / Strahler based catchment break-up of a particular order to discretise the catchment. This would remove the subjectivity in selecting the number of subcatchments to use and their outlet locations, thus offering a more objective approach to catchment discretisation.

4.9 NODAL NETWORK ARRANGEMENT

All subcatchments that are delineated are automatically networked by CatchmentSIM to provide hydrologic connectivity. This ensures that CatchmentSIM projects are compatible with 'downstream' hydrologic and hydraulic models which may be coupled with the software. An example of the subcatchment networking methodology and associated labelling is illustrated in **Figure 4-19**.

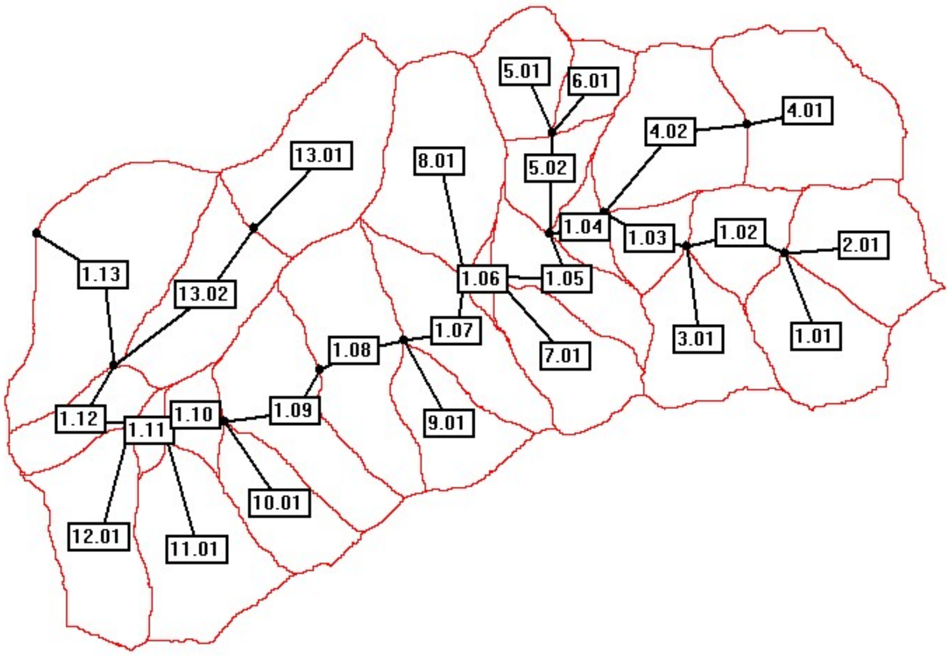


Figure 4-19 : Sample CatchmentSIM Nodal Network Arrangement

The labelling methodology is designed to identify the significance of the upstream tributary to the left of the decimal point, and the subcatchment position in the tributary network to the right of the decimal place. A number of options are available to customise the labelling approach. These include determining the tributary significance based on decreasing maximum stream length rather than in downstream order of lateral influx and using alphabetic letters instead of integers to the right of the decimal point.

4.10 URBANISATION TOOLS

CatchmentSIM includes a range of tools designed to accommodate representation of urban areas in a project. Firstly, CatchmentSIM allows calculation of impervious area proportions for subcatchments which is a parameter required for almost all hydrologic models. Furthermore, CatchmentSIM offers a more comprehensive method of urban analysis. Realistic modelling of runoff in urban areas requires consideration of the numerous processes that may be in play during a rainfall event in an urbanised catchment. These processes may include roof, downpipe, fencing, roads, footpaths, gutters and piped drainage systems (Goyen and O'Loughlin 1999). CatchmentSIM accommodates individual representation of several of these processes by modelling individual flow path deviations occurring as a result of urban hydraulic controls such as roads, gutters and channels networks.

4.10.1 Impervious Area Database

CatchmentSIM provides capability for a database of impervious areas to be maintained within each project. This database can be constructed by drawing impervious area polygons on the screen or importing them from external GIS databases. These polygons can each have a description, percentage impervious and on / off state. Users can simply turn individual polygon on or off, alter their attributes or group select and manipulate them based on particular attributes (*such as selecting all polygons labelled as 'Road'*). An example of the impervious area database can be seen in **Figure 4-20**.

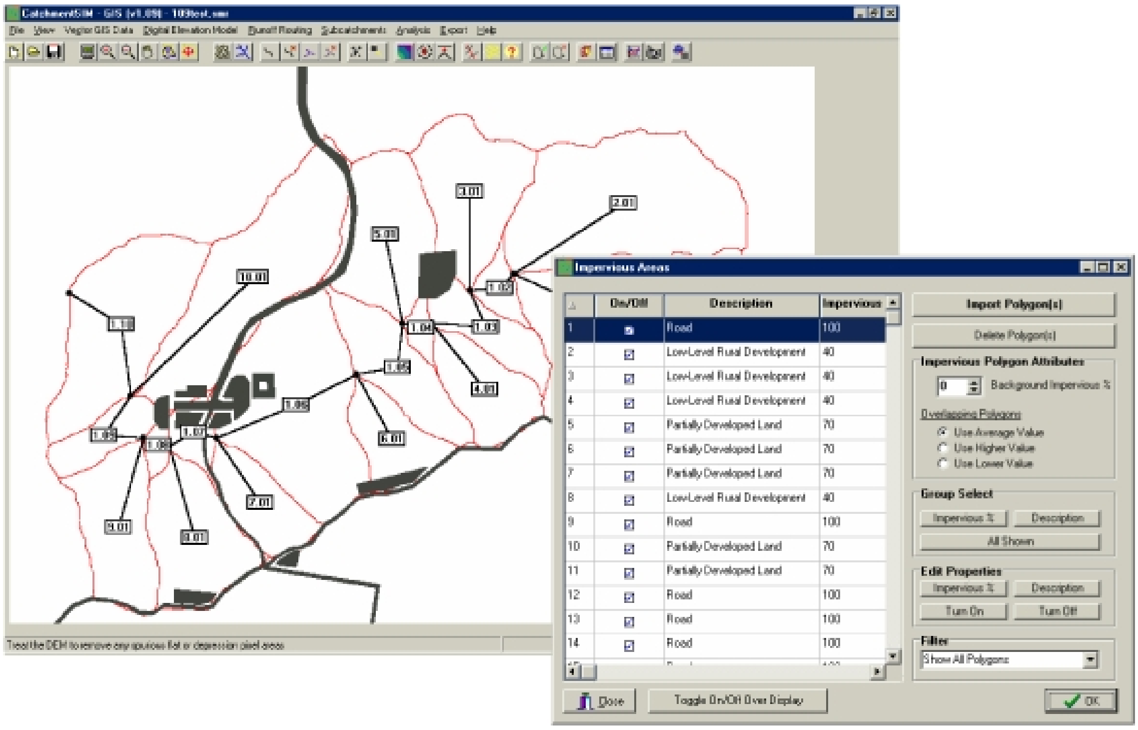


Figure 4-20 : Impervious Areas Database

CatchmentSIM can accommodate complex polygons such as concave or convex polygons, or multi-region (*island*) polygons. An example of an island polygon can be seen in **Figure 4-21** as well as in **Figure 4-20** *(closest to the 1.06 subcatchment label*). CatchmentSIM will automatically calculate impervious percentages for each subcatchment based on the impervious area polygons, their individual impervious proportions, and the background impervious proportion. The background impervious proportion is an impervious proportion that is applied to all areas outside of the impervious area polygons. This value is designed to represent sporadic impervious areas such as rocky outcrops etc, it may be set at any value between 0 and 100%. CatchmentSIM calculates impervious areas by determining which DEM cells are within impervious area polygons and tallying their area multiplied by the impervious proportion assigned to the impervious area polygon. The algorithm CatchmentSIM utilises to determine if a DEM cell is within a polygon is based on constructing a horizontal line in one direction from the centroid of the DEM cell and counting the number of intersections with the polygon boundary. An odd number of intersections indicates that the DEM cell is within the polygon whereas 0 or an even number of intersections indicates that the DEM cell is outside the polygon boundary (*or inside an island*).

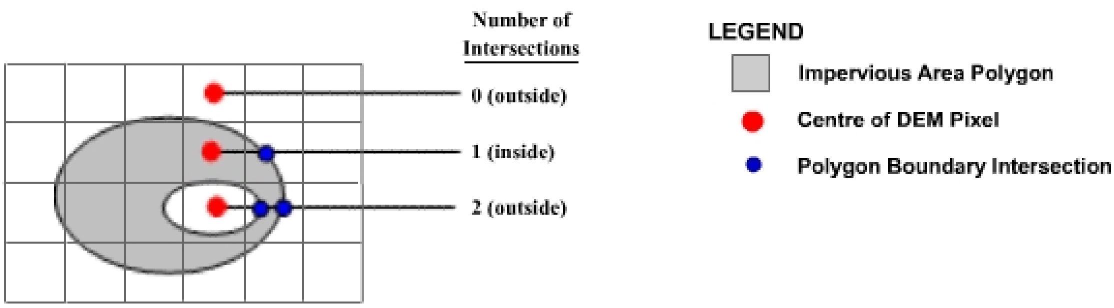


Figure 4-21 : Rasterisation of Impervious Area Polygons

4.10.2 Modelling of Hydraulic Structures

CatchmentSIM includes a number of tools to help model flow paths in urban environments. Urban structures have a significant effect on flow paths in urban areas and they are usually not represented in source GIS data such as DEMs or contour and stream alignments. As such, they need to be added into a CatchmentSIM project as an addition to the source GIS data. This can be achieved by one of two approaches. Firstly, the urban structures can be hard-coded into the DEM by changing the elevations of relevant DEM cells to cause flow paths to act in a realistic manner in the vicinity of urban structures. Alternatively, urban structures can be modelled in CatchmentSIM as supplementary objects that control flow paths when they intersect the alignment of an urban structure. Modelling urban structures in this was does not require the DEM cell elevations to be altered. Furthermore, each individual urban control can be turned on or off, and flow paths and subcatchment layouts may be regenerated easily. This is valuable when analysing drainage studies for hydrologic events of differing magnitudes where particular urban structures may only be relevant for certain storm magnitudes, or during flood mitigation scenario analysis.

CatchmentSIM accommodates both of these modelling approaches. An example of hard-coding urban structures into the DEM is presented in **Figure 4-22**, where road crown alignments were hard-coded into DEM by raising all cells along the road crowns by 0.5 metres using CatchmentSIM's vector data set operations. The PFS algorithm was then applied to remove resultant flat and pit cells and breach the road crowns at their points of lowest elevation.

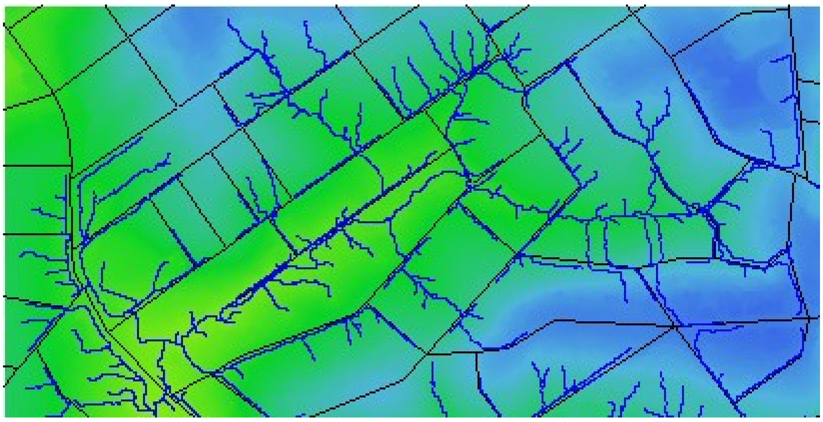
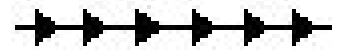
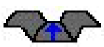


Figure 4-22 : Effect of Hard-Coding of Road Crowns on Stream Network

As shown in **Figure 4-22**, the calculated stream network has been strongly affected by the hard-coding of urban structures. For more detail on how hard-coding of urban structures can aid hydrologic modelling, see the Holland Park Local Stormwater Management Plan case study shown in Section 6.2 (*page 198*).

Alternatively, urban structures can be modelled separately using CatchmentSIM's hydraulic control tools. These tools allow representation of channels and gutters in a CatchmentSIM project that act as overriding flow controls. These hydraulic controls are described in the following sections.

4.10.3 Channel Type Hydraulic Controls

Channel type hydraulic controls are drawn in CatchmentSIM as a solid line with triangles pointing in the direction of the line towards the channel outlet  and by one of the following symbols in the Hydraulic Controls Form  or . These controls have the effect of forcing flow paths that intersect these controls to follow the channel until its outlet point regardless of whether this involves upstream flow, or flow in a direction that does not represent the steepest downslope direction at that point in the DEM. These hydraulic controls should be used when a user wishes to completely override the DEM and force flow to follow a pre-determined path. Channel type hydraulic controls should be used to represent drainage channels or urban flow paths that are not represented in the DEM or source contour data. A stream network can also be imported as channel type hydraulic controls to force flow to follow an existing stream network as shown in **Figure 4-23**.

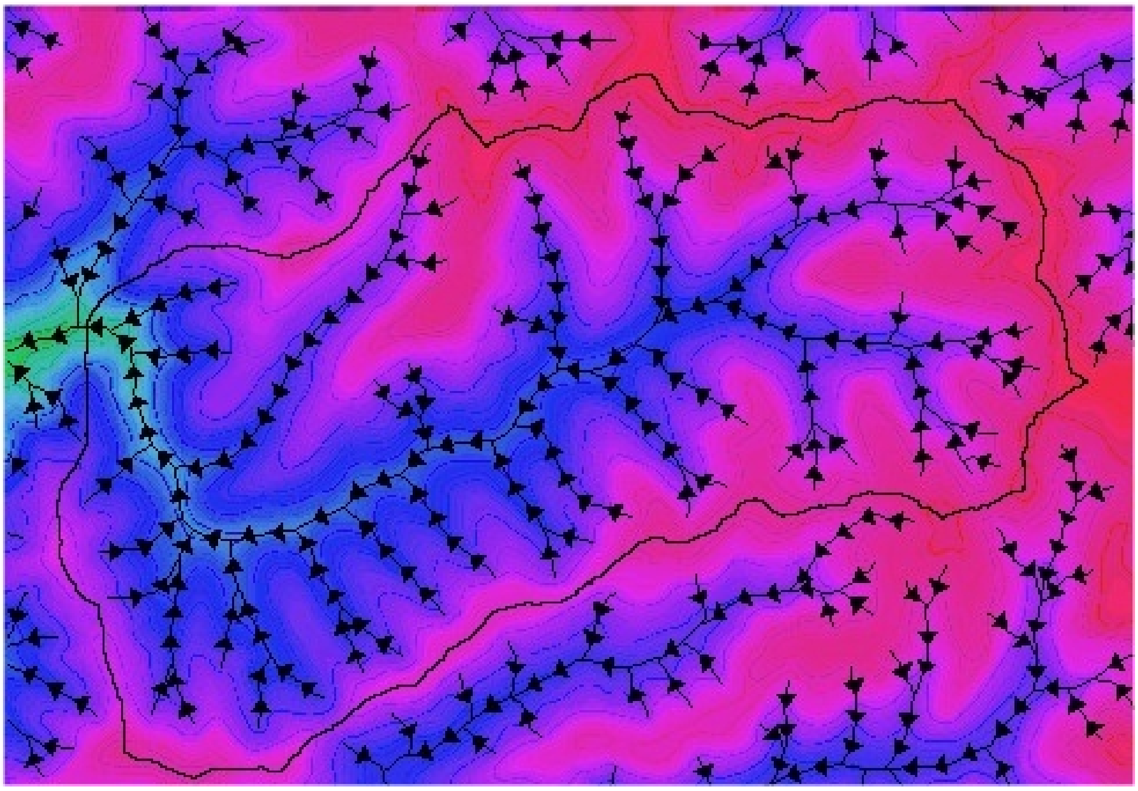


Figure 4-23 : Using a Stream Network as Channel Hydraulic Controls

4.10.4 Gutter Type Hydraulic Controls

Gutter type hydraulic controls are drawn in CatchmentSIM as a solid line with triangles pointing at a perpendicular angle to the direction of the line  and by one of the following symbols in the Hydraulic Controls form  or . The triangles point in the direction in which flow is allowed to pass over the hydraulic control.

When a flow path intersects a gutter type hydraulic control, flow will still follow the DEM calculated steepest descent within restrictions imposed on the flow direction by the gutter. If the flow direction would see the flow path crossing the gutter (*against the direction of the arrows*) then it is restricted from doing so. Instead, flow is allowed to travel along the gutter provided this direction represents a downslope gradient. If neither of the along-gutter directions are downslope then the flow path is trapped. The gutter processing algorithm will then search along the gutter in both directions within a specified tolerance for a cell of lower elevation. If such a cell is found within the tolerance then the flow path will be mapped to this point, and the algorithm is re-applied at the new location. The tolerance may be in the form of a set number of cells or a set elevation. The effect of this algorithm is to simulate ponding at low points behind gutters which would in reality fill the cell elevation and allow flow to progress to cells of higher elevation provided they are lower than the height of the gutter. The gutter height is simulated in CatchmentSIM by utilising an elevation tolerance. If a cell of lower elevation is not found within the specified tolerance then a hydraulic breach is formed and the flow path is permitted to breach the gutter. This can be seen in **Figure 4-24** where flow paths travel along the gutter until the searching algorithm fails to find a suitable downslope cell along the structure and a hydraulic breach occurs.

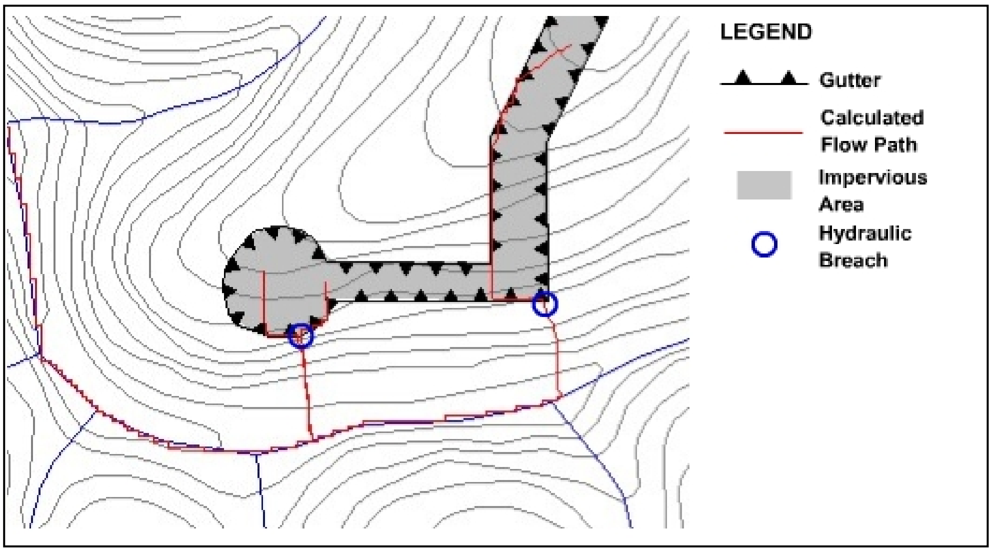


Figure 4-24 : Hydraulic Representation of Gutters

4.11 HYDROLOGIC ANALYSIS TOOLS

A range of hydrologic analysis tools have been incorporated into CatchmentSIM to aid users in understanding the differing hydrologic properties of subcatchments within their project. These tools include parameter calculation and charting capabilities. The CatchmentSIM subcatchment attributes table is calculated automatically and lists the following parameters for each subcatchment:

- **Subcatchment Number :** Integer ID of the subcatchment, used instead of subcatchment name when the subcatchment network is discontinuous (*ie., more than one catchment outlet*).
- **Subcatchment Name :** Subcatchment name assigned in nodal network arrangement (*see Figure 4-19, page 154*).
- **Subcatchment Area (ha) :** Subcatchment area expressed in hectares as calculated by addition of all cells within subcatchment multiplied by cell area.

- **Downstream Subcatchment Name :** Subcatchment name of immediately downstream subcatchment.
- **Subcatchment Slope (%) :** Subcatchment slope as calculated by average of all average vectored slope calculations (*see Figure 5-8, page 183*) for each cell on the perimeter of subcatchment.
- **Impervious Area (ha) :** Impervious area within subcatchment as calculated by rasterisation of impervious polygons, and consideration of background impervious parameter (*see Section 4.10.1, page 155*).
- **Impervious Proportion (%) :** Impervious proportion of subcatchment as calculated by impervious area (*above*) divided by total area expressed as a percentage.
- **Raster Drainage Density (%) :** Raster drainage density as calculated by stream cells divided by total subcatchment cells expressed as percentage.
- **Perimeter Length (km) :** Length of the subcatchment perimeter formed by combination of outer edge lengths of all subcatchment perimeter cells.
- **Horton Drainage Density (km^{-1}) :** Horton drainage density as calculated from the vector stream network length within the subcatchment divided by subcatchment area.
- **Bifurcation Ratio :** Bifurcation ratio calculated for subcatchment based on vector stream network as illustrated in **Figure 5-5** (*see page 179*).
- **Main Stream Length (km) :** For self-contained subcatchments (*ie., no upstream input*) the main stream length is defined as the longest flow path in the subcatchment. For subcatchments with one or more upstream input

subcatchments, the main stream length is defined as the longest stream segment within the subcatchment which is from an upstream subcatchment.

- **Main Stream Slope (%) :** The average vectored slope of the main stream defined above, expressed as a percentage.
- **Shape (dimensionless) :** The shape parameter is defined as the subcatchment area divided by the perimeter length squared and is dimensionless ($\frac{km^2}{(km)^2}$).

CatchmentSIM includes a range of charts to help investigate the hydrologic properties of subcatchments, these include :

- Downslope flow path long-sections;
- Cross-section charting;
- Downstream flow distance vs proportion of in-stream cells;
- Stream Area Threshold (SAT) vs raster drainage density;
- Stream order vs stream numbers (*bifurcation*);
- Cumulative stream length vs stream order;
- Relative area vs relative height (*hypsometric curve*);
- Stream order vs channel drop; and,
- Stream Area Threshold (SAT) vs stream drop relationship vs bifurcation.

More information and an in-depth description of how these charts can be used to examine subcatchment hydrologic characteristics is given in Section 5.4 (*page 181*).

CatchmentSIM also has the ability to generate animations of parameter variation over a catchment. An example of this is the variation of raster stream cells with SAT which can be seen on the Data CD enclosed as **Appendix E**.

4.12 COUPLING WITH 3RD PARTY APPLICATIONS

As outlined in Section 2.10 (*page 78*), the vast amount of hydrologic and topographic information that can be produced by automated hydrologic analysis of DEMs is not useful unless it can be transitioned into any 'downstream' modelling software that a user may wish to apply. This process is called coupling and is accommodated in CatchmentSIM by a flexible internal result export macro language. This language is called CSTalk and enables the creation of input files for any computer software package regardless of its operating system (*UNIX, Windows*) or file type (*binary or text*).

Many coupling scripts are distributed with the CatchmentSIM software and additional scripts are available on the project website. Some of the 3rd party applications that can be coupled with CatchmentSIM using the aforementioned macro scripts include:

- Runoff Analysis & Flow Training Simulation (RAFTS-XP)
- Watershed Bounded Network Model (WBNM)
- RORB
- URBS
- Hydrologic Modeling System (HEC-HMS).
- DRAINS

CSTalk scripts can also be written by the user to allow integration with in-house software applications or 3rd party software applications that do not yet have available CSTalk scripts. A number of users have developed their own CSTalk scripts and some of these are also available on the website. These include:

- A modified version of the URBS script developed by the Bureau of Meteorology in Brisbane, Australia by David Stephens and Terry Malone. They developed this script to be compatible with in-house software for rainfall interpolation.
- A modified version of the RAFTS-XP scripts developed by David Tetley from Patterson Britton & Partners in Sydney, Australia. This script was developed to accommodate an alternative type of subcatchment routing of impervious areas.

The coupling methodology provided by the CSTalk language is illustrated in **Figure 4-25**. A manual and reference guide for writing CSTalk scripts has also been developed and is attached as **Appendix B**.

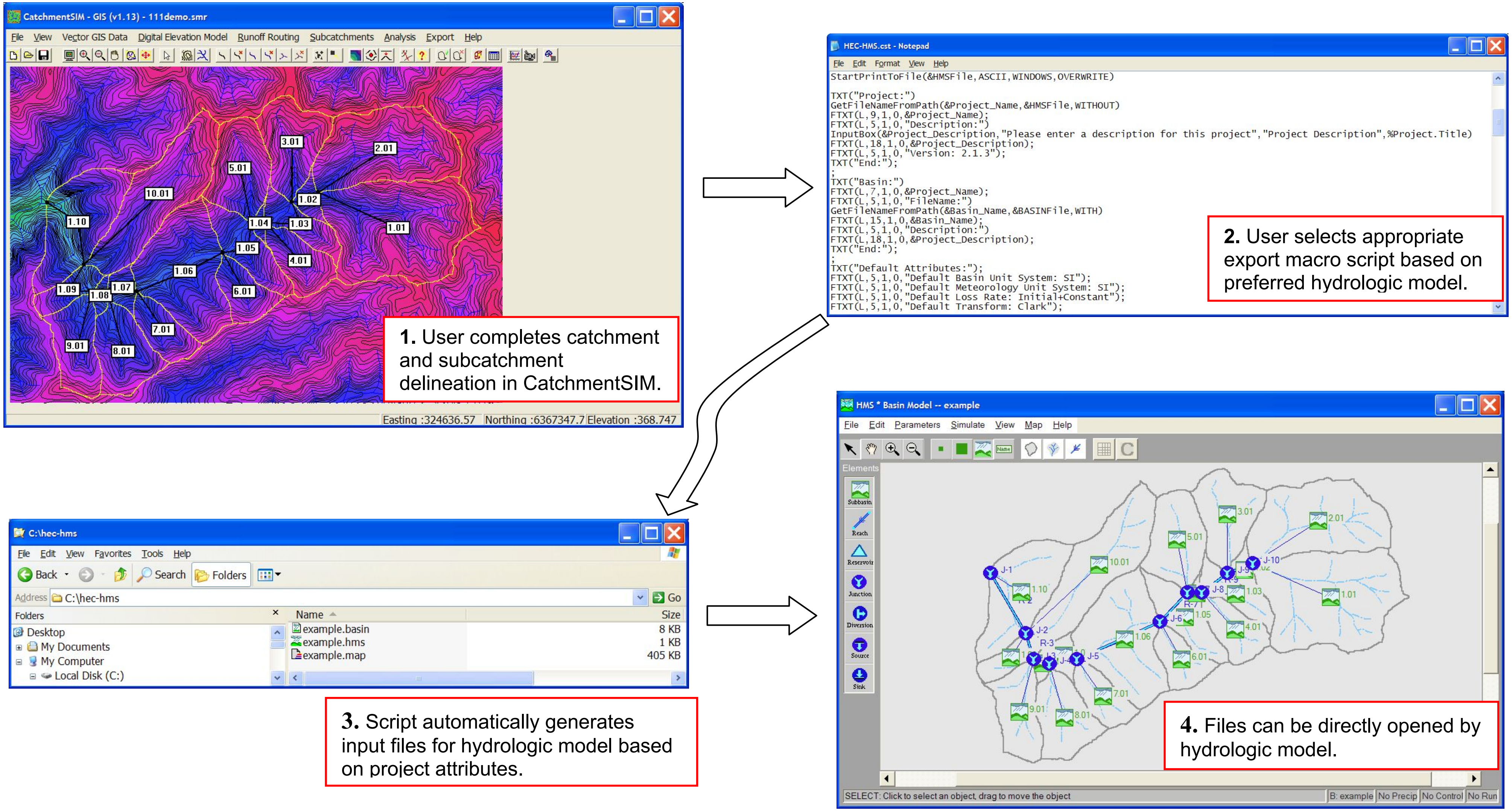


Figure 4-25 : CatchmentSIM Coupling Methodology

Since CSTalk scripts can produce files in any format, they are also commonly used to develop standardised report formats for professional organisations. For example, David Tetley from Patterson Britton and Partners developed a CSTalk script that automatically generates a Rich Text File (*.rtf) with the standardised report template shown in **Figure 4-26**. The data columns that cannot be read directly from a CatchmentSIM project, such as rainfall loss coefficients are obtained through a series of script-generated dialog boxes.

Hydrologic Model Parameters

Hydrologic Model Node	Sub-Catchment Area (ha)	Catchment Slope (%)	Impervious Areas				Pervious Areas				% Impervious
			Impervious Area (ha)	Mannings 'n'	Initial Loss (mm)	Continuing Loss (mm/hr)	Pervious Area (ha)	Mannings 'n'	Initial Loss (mm)	Continuing Loss (mm/hr)	
1.10	617.4	20.8	0.0	0.015	1	0	617.4	0.035	10	2.5	0.0
10.01	755.0	19.2	41.3	0.015	1	0	713.7	0.035	10	2.5	5.5
1.09	154.2	20.4	2.1	0.015	1	0	152.1	0.035	10	2.5	1.4
9.01	352.1	21.0	5.2	0.015	1	0	346.9	0.035	10	2.5	1.5
1.08	43.4	19.0	4.0	0.015	1	0	39.3	0.035	10	2.5	9.3
8.01	391.9	16.4	16.7	0.015	1	0	375.2	0.035	10	2.5	4.3
1.07	89.2	19.5	23.7	0.015	1	0	65.5	0.035	10	2.5	26.6
7.01	224.6	21.0	9.8	0.015	1	0	214.9	0.035	10	2.5	4.3
1.06	796.2	11.2	63.2	0.015	1	0	733.0	0.035	10	2.5	7.9
6.01	222.1	12.6	11.6	0.015	1	0	210.5	0.035	10	2.5	5.2
1.05	302.4	12.4	0.6	0.015	1	0	301.8	0.035	10	2.5	0.2
5.01	444.4	17.8	28.3	0.015	1	0	416.1	0.035	10	2.5	6.4
1.04	31.8	12.1	0.6	0.015	1	0	31.2	0.035	10	2.5	1.8
4.01	263.7	13.7	3.2	0.015	1	0	260.4	0.035	10	2.5	1.2
1.03	210.9	10.8	8.5	0.015	1	0	202.4	0.035	10	2.5	4.0
3.01	438.4	17.5	5.4	0.015	1	0	433.0	0.035	10	2.5	1.2
1.02	76.7	9.9	0.0	0.015	1	0	76.7	0.035	10	2.5	0.0
2.01	867.6	11.5	0.0	0.015	1	0	867.6	0.035	10	2.5	0.0
1.01	1184.3	8.2	16.8	0.015	1	0	1167.5	0.035	10	2.5	1.4

Figure 4-26 : Sample CST Script Generated Report

This method of generating standardised reports represents a fully customisable technique to create tailored reports and analysis which can be replicated over a wide range of projects. It is much quicker than manual development of such tables which is the normal approach and also eliminates data entry errors.

CatchmentSIM's coupling language is a simple text language that can be easily mastered by most users. It allows seamless coupling between CatchmentSIM and any other software which has a published file format. Software products that do not have published file formats usually have input file formats that are published. Hence, CatchmentSIM can usually be coupled with these applications.

4.13 CONCLUSION

As outlined in the preceding sections, a software application, termed CatchmentSIM, has been developed to meet the design objectives outlined in Chapter 3. This software incorporates algorithms for the interpolation of a raster DEM from contour and watercourse alignment data. These algorithms include advances on current implementations of profile based DEM interpolation algorithms by utilising variable vector search ray frequency and flat cross-section discounting. The watercourse integration algorithm enables non 3D information to be incorporated into the DEM and ensures that valley areas are accurately defined within the DEM, which effectively preserves the observed stream network in the project.

Flat and pit cells may then be removed from the DEM using an iterative filling algorithm or an advanced PFS based breaching algorithm. The PFS algorithm is based on the work of Jones (2002) but has been improved by incorporation of a number of modifications including elevation prioritised processing and 3 parameters (*see page 141*) designed to optimise the speed and accuracy of the algorithm.

CatchmentSIM's flow routing algorithm is based on the research of Lea (1992). However, important modifications have been made to increase speed and ensure flow paths can no longer travel towards, or cross into, cells of higher elevation. The modified version of the flow routing algorithm accurately models flow paths on hill-slopes and within channels (*as demonstrated in Section 5.2, page 172*). Furthermore, since multiple flow direction algorithms switch to the D8 method in stream channels (*using the maximum cross grading area parameter*), it is the only algorithm that allows for generation of stream networks that are not based on the D8 method.

CatchmentSIM's flow routing algorithm has flow-on improvements in many subsequent parts of an analysis including automated catchment break-up and hydrologic analysis. Due to the algorithm's accurate calculation of flow path length statistics, a number of new charting and analysis functions may be introduced which are not available using other flow routing algorithms.

The urban tools incorporated within CatchmentSIM allow for the software to be applied in regions where the DEM is not entirely representative of the local flow constraints which is commonly the case in urban areas. These tools enable processing of urbanised catchments that would otherwise be difficult, if not impossible, for application by such techniques. The functionality that these tools provide is unique to CatchmentSIM and is not available in any of the other software packages reviewed in Section 2.11 (*page 84*).

The CSTalk macro language provides a simple method for coupling of CatchmentSIM with any hydrologic or hydraulic computer model. Furthermore, the language provides for the automatic generation of customised report formats improving quality control and eliminating data transfer errors. The development of CSTalk scripts for Australian hydrologic models such as RAFTS-XP, WBNM, RORB, URBS and DRAINS provides the first available GIS coupling capabilities for many of these programs.

Chapter 5 presents verification exercises for several of the CatchmentSIM algorithms, as well as techniques for applying the hydrologic and geomorphologic analysis tools within CatchmentSIM to gain a better quantitative understanding of the hydrologic properties of subcatchments within a lumped hydrologic model.

5 ASSESSMENT OF ALGORITHMS

5.1 INTRODUCTION

This chapter will compare some of the algorithms outlined in Chapter 4 with currently available algorithms for hydrologic analysis of DEMs. Furthermore, it will also present a demonstration of how CatchmentSIM's hydrologic and geomorphologic analysis tools can be used to derive additional knowledge about the properties of subcatchments within a project. This knowledge can be utilised to enable a better understanding and conceptual basis for assignment of non-physical parameters in 'downstream' hydrologic or hydraulic computer models.

5.2 COMPARISON OF FLOW ROUTING METHODS

The flow routing algorithm is one of the most important algorithms for automated hydrologic analysis of DEMs. To verify the hydrologic accuracy of the CatchmentSIM flow routing algorithm outlined in Section 4.6 (*page 143*), comparative tests were undertaken with the D8 method.

The flow paths generated by the D8 algorithm and the CatchmentSIM algorithm for 6 sample points in a catchment are compared in **Figure 5-1**, superimposed over the contours used to interpolate the DEM.

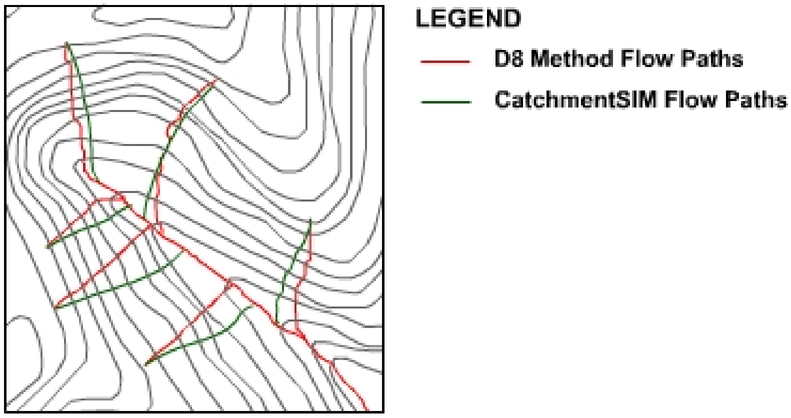


Figure 5-1 : D8 Flow Paths vs CatchmentSIM Algorithm

It can be seen in **Figure 5-1** that significant deviations in the calculated flow paths exist for several of the sample points. The tendency of the D8 method to snap to cardinal or diagonal direction due to its limitation of eight potential directions can be clearly seen in the lower left sample points. In these cases the D8 flow paths are snapping to 45 degree lines since this is the closest approximation to local slope that the D8 algorithm can generate. The CatchmentSIM flow paths originating from these sample points can be seen to flow perpendicular to the contours. Consequently, they are likely to be more hydrologically accurate.

The effect of the errors associated with the D8 method can be seen to follow through into subcatchment delineation. The subcatchment boundary delineated from the same outlet point using the D8 and CatchmentSIM flow routing algorithm can be seen in **Figure 5-2**.

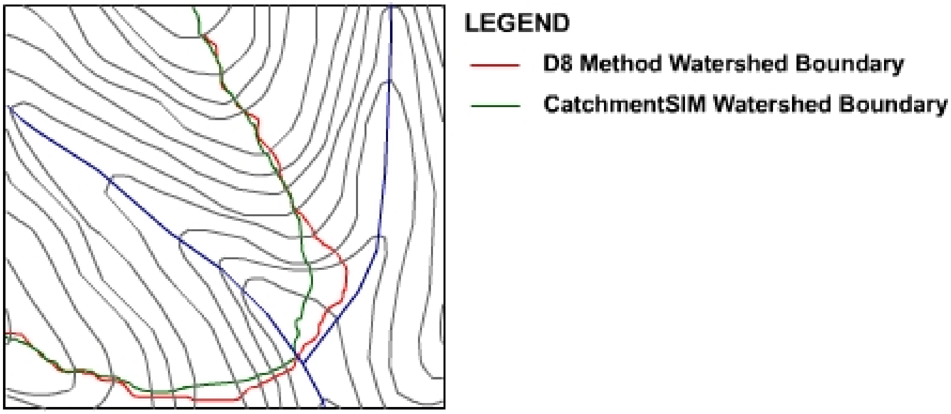


Figure 5-2 : Basin Delineation, D8 Method vs CatchmentSIM

The tendency of the D8 method to snap to diagonal and cardinal directions can again be seen in **Figure 5-2**, where the D8 generated boundary is biased towards the 45° angle and does not correctly identify the ridge line between the stream confluences. As shown in **Figure 5-2**, the two algorithms converge when they reach more defined ridge lines with stronger contour curvature. As such, the error introduced by the D8 method will be more pronounced in the outlet areas of subcatchments. The significant problem with quantifying this error is that it will be a function of the size of the subcatchment being delineated. This is because the length of the subcatchment boundary segment that does not follow major ridge lines will become a larger proportion of the total subcatchment boundary as subcatchment area decreases. As a result, the proportional error associated with the D8 method will become more pronounced the higher the discretisation of the catchment. This is an undesirable attribute of the method because higher catchment discretisation is usually undertaken to facilitate more accurate hydrologic modelling. Thus, if the D8 method is being applied then a user may inadvertently be introducing greater errors while attempting to gain greater accuracy.

5.3 STREAM NETWORK ANALYSIS

As documented in Section 4.7 (*page 145*), CatchmentSIM is the only product currently available that allows for development of a connected vector stream network that is based on a more hydrologically accurate flow routing algorithm than the D8 method. Furthermore, CatchmentSIM includes Horton / Strahler ordering and associated geomorphologic and fractal coefficients. One of the key advantages of this method of stream network generation is that it facilitates a significant amount of hydrologic analysis to help users develop a better understanding of the hydrologic characteristics of the catchment and its subcatchments.

The first step in development of a stream network is assignment of the relevant SAT / MSCL parameters. This is usually undertaken arbitrarily or based on closest match to an observed stream network. However, CatchmentSIM allows for geomorphological assessment of the derived stream network to ensure that it conforms with accepted stream power laws. CatchmentSIM also includes tools to amend the selected SAT / MSCL parameters in order to derive a more geomorphologically realistic stream network, as outlined in the following sections.

5.3.1 Quantitative Analysis of Stream Area Threshold

CatchmentSIM offers a range of analysis tools to help quantitatively assess the appropriate SAT for stream network generation. This is based on the law of constant mean stream drops as first observed by Broscoe (1959). As outlined in Section 2.8.1 (*page 66*), this law states that the mean drop of streams of different Strahler orders should be statistically similar. Tarboton (1997) suggests comparing the 1st order mean stream drop to the mean stream drop of all other streams using Student's t-test with a 95% confidence interval (*ie., $T \approx 2$*). The lowest SAT that yields a stream network that has statistically similar means within this confidence interval should be applied. Alternately, the MSCL can be adjusted with a highly detailed stream network until Student's T value is less than 2. CatchmentSIM can chart the mean stream drop scatter for a generated stream network as shown in **Figure 5-3**.

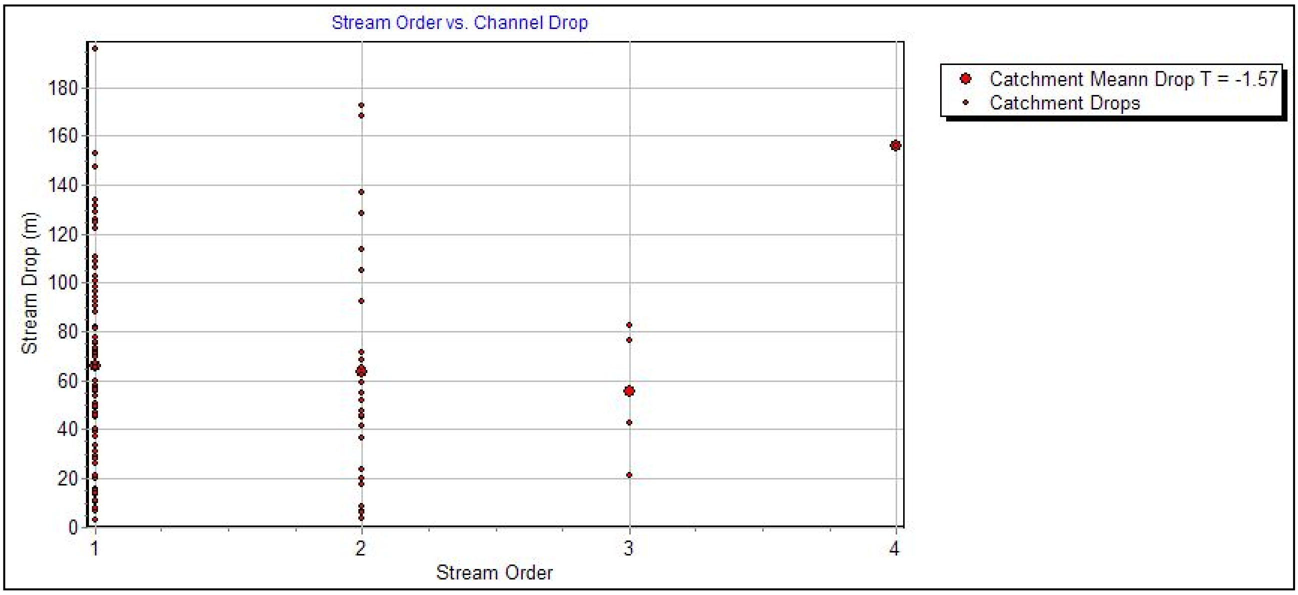


Figure 5-3 : CatchmentSIM Charting of Stream Drop Scatter

In **Figure 5-3**, the small circles represent the individual stream segment elevation drops while the larger circles represent the mean elevation drop for that order. It can be seen in the legend that the calculated Student's T value for this stream network is -1.57

which is well within the 2.00 95% confidence interval. Hence, the stream network generated at this SAT (*500 cells*) does obey the law of constant mean stream drops. In order to help the user identify the appropriate SAT for use in an analysis, CatchmentSIM also enables the Student's T value to be calculated for a range of SAT derived stream networks and displayed as a chart. The same project used in **Figure 5-3** was used to generate **Figure 5-4** shown below. It can be seen that the general trend is for the Student's T value (*left axis*) to reduce as SAT increases. This means that SAT values smaller than 500 produce stream networks that do not obey the law of constant mean stream drops within the 95% confidence interval. This chart can be used to evaluate the minimum SAT that can be applied with confidence. The chart also indicates the catchment bifurcation ratio for these stream network which stays quite constant for the range of stream networks analysed.

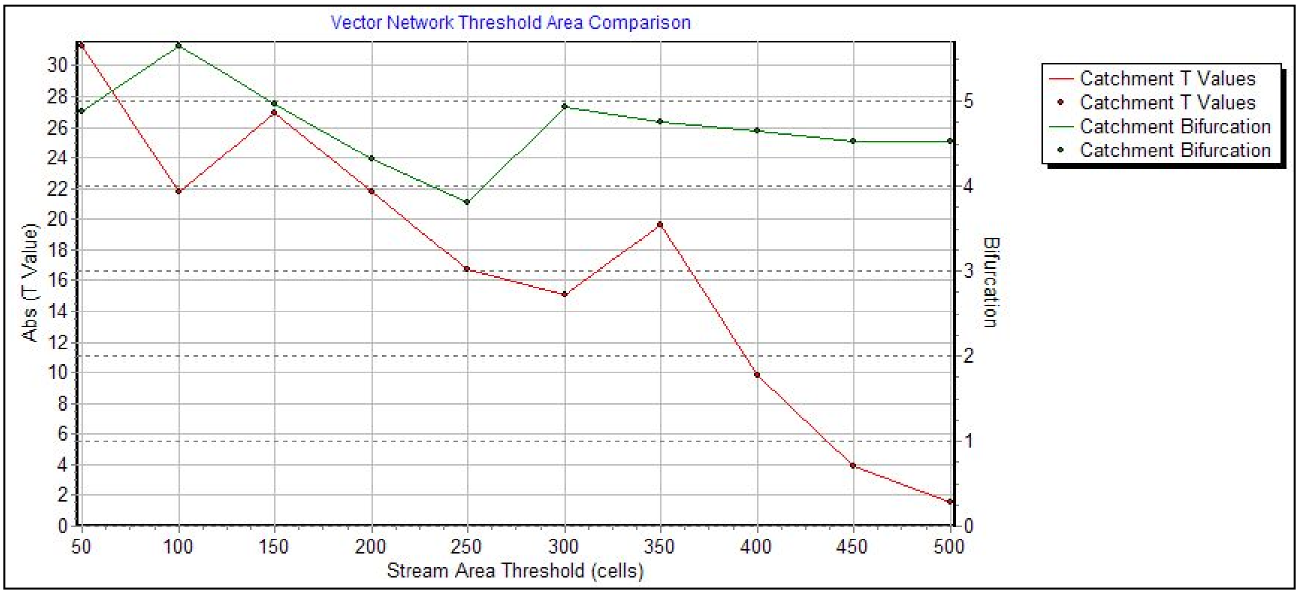


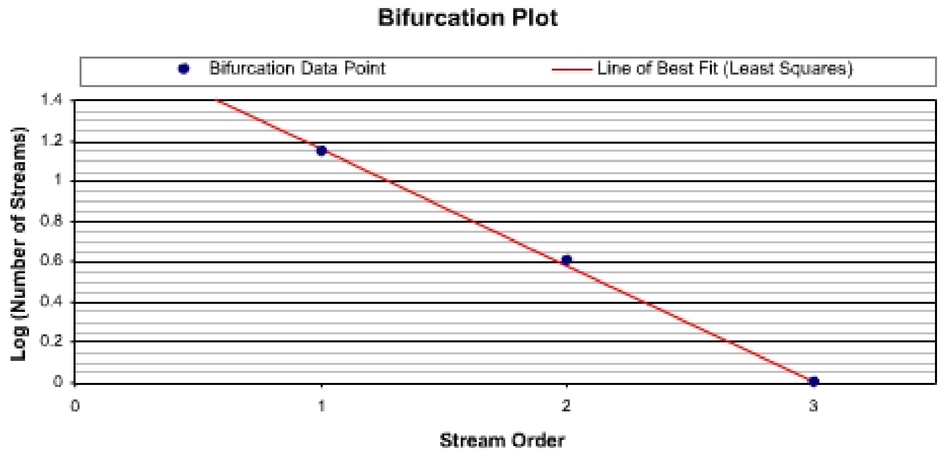
Figure 5-4 : CatchmentSIM Charting of SAT vs Student's T Value

For the example presented in **Figure 5-4**, it can be seen that the Student's T-value trend line crosses the threshold value of 2.0 at approximately 490 cells. Thus, 490 cells is the minimum SAT value that should be used in order to generate a stream network that conforms to the law of constant mean stream drops.

TauDEM is the only other software package that offers the capability to analyse stream drops and it does not provide the charting capabilities illustrated in **Figure 5-3** and **Figure 5-4**. Furthermore, the TauDEM analysis is based on a D8 generated stream network which will have inherited the inaccuracies of the D8 flow routing algorithm.

5.3.2 Analysis of Stream Network Topology

Horton / Strahler ordering provides the functionality to derive some key geomorphologic and fractal stream network coefficients, that can be used to examine the hydrologic properties of subcatchments. Strahler's revision of Horton's method of stream ordering is documented in Section 2.9.2 (*page 75*) and illustrated in **Figure 2-25** (*page 77*). Once streams have been defined as a specific order, a number of useful parameters and geospatial statistics can be calculated. The most important of these is the bifurcation ratio which is a measure of the relationship between the numbers of streams of different orders. Strahler found that a strong log-normal relationship exists between the logarithms of the number of streams of each order versus stream order. The gradient of this relationship is deemed the bifurcation of the subcatchment. **Figure 5-5** shows the calculation of the bifurcation for the sample catchment illustrated in **Figure 2-25** (*page 77*).



Stream Order	Number Of Streams	Log (Number of Streams)
1	14	1.146
2	4	0.602
3	1	0.000

Line of Best Fit

Log(# Streams) = -0.573x (Stream Order) + 1.729

Bifurcation Ratio

Bifurcation Ratio = 10 ^ $^{(-1 \times -0.573)}$ = <u>3.74</u>

Figure 5-5 : Calculation of Bifurcation Ratio

CatchmentSIM can automatically calculate the bifurcation ratio for the catchment and all subcatchments, as well as a number of related parameters such as Horton drainage density. Interestingly, Strahler's work on topographic maps found strong bifurcation relationships, with bifurcation ratios that were consistently within the range of 3-5. It has been found that CatchmentSIM generated vector stream networks also exhibit this strong relationship, with bifurcation ratios also around this range. This lends weight to the argument that vector stream networks generated over DEMs can closely resemble the fractal nature of natural systems.

One of the unfortunate attributes of all techniques for analysis of stream networks is that most derived parameters are dependent on the SAT value adopted for generation of the stream network. However, it has been found that the bifurcation ratio is not highly dependent on the SAT value used to generate the network. This is illustrated in **Figure 5-6,** which shows the bifurcation ratios calculated for two different subcatchments for a range of vector stream networks calculated at different SAT values.

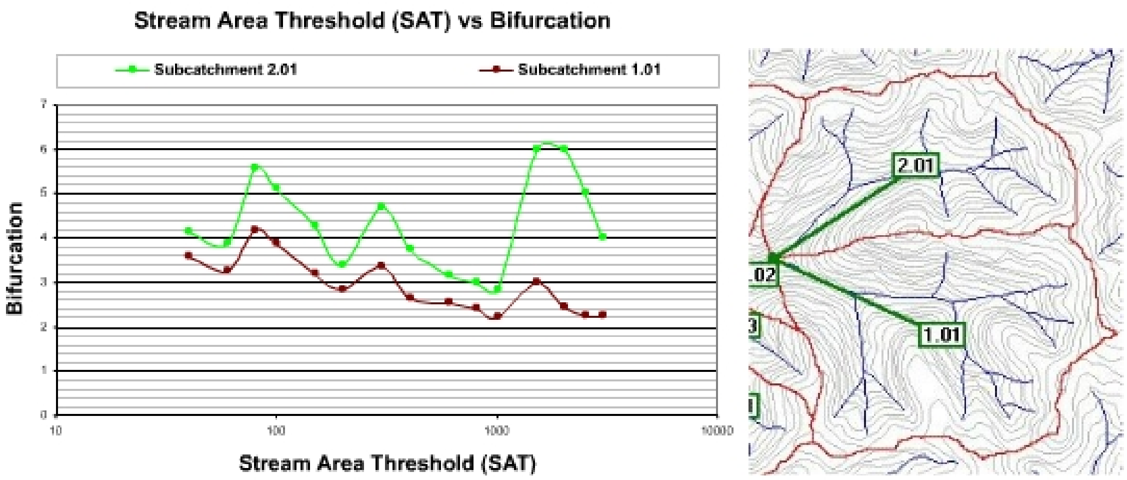


Figure 5-6 : SAT vs Bifurcation Relationship for Two Subcatchments

It can be seen in **Figure 5-6** that there does not appear to be a strong trend in each of the Bifurcation vs SAT plots. This fact is useful because it implies that deviations in bifurcation ratios across subcatchments within a model may convey important information about the hydrologic properties of the subcatchments and not simply be a function of the adopted SAT value.

For example, in **Figure 5-6**, it can be seen that regardless of the SAT value used to generate the vector stream network the bifurcation ratio for subcatchment 2.01 is significantly higher than subcatchment 1.01. The implications of this relationship means that subcatchment 2.01 has a greater proportion of 1st order streams than subcatchment 1.01 (*bifurcation plot will be steeper*) and the drainage network is more fractal. This information has important hydrologic implications and may mean that subcatchment 2.01 will respond quicker to rainfall and may need to be allocated a smaller lag time or related lag coefficient in any 'downstream' hydrologic or hydraulic model.

5.4 OTHER TYPES OF HYDROLOGIC ANALYSIS

Aside from vector stream network analysis, CatchmentSIM includes a number of other hydrologic analysis tools to help quantify relationships between various subcatchments and even individual cells. The following sections outline some of the key charting abilities of CatchmentSIM, and demonstrate how these charts can be interpreted to help characterise the hydrologic properties of subcatchments.

5.4.1 Drainage Long-Section Profiles

One of the most commonly utlised parameters in hydrologic models is average subcatchment slope. Traditionally, this is commonly calculated by 'back-of-the-envelope' calculations such as the 85-15 rule which measures the linear slope between points along a single flow path at the 15% and 85% of flow path length positions. Such short-cut calculations not only assume that these points are representative of the average vectored slope for this profile, but also assume that the adopted flow path is representative of the entire subcatchment. Average vectored slope is defined by the slope of the straight line that bisects the flow path profile causing equal areas between the profile and slope line above and below the slope line. For example, consider the slope profile shown in **Figure 5-7**.

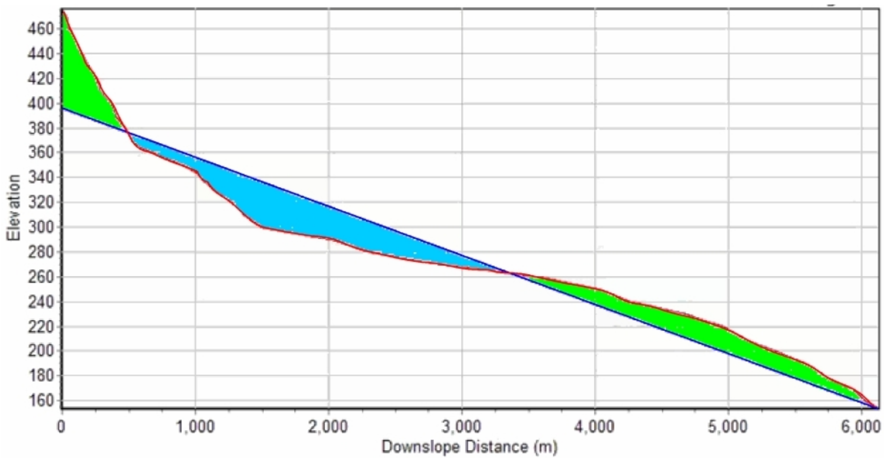


Figure 5-7 : Average Vectored Slope Methodology

In **Figure 5-7**, the average vectored slope is the slope of the blue line which is fitted by ensuring that the combined area of the green regions is equal to the area of the blue region. To calculate average vectored slope correctly by hand is a tedious and iterative process. Furthermore, the assumption still remains that the chosen flow path is representative of the subcatchment. CatchmentSIM automates the process of calculating average vectored slope from any point in the catchment to the nearest subcatchment outlet, or major catchment outlet, and generates charts such as that shown in **Figure 5-8**.

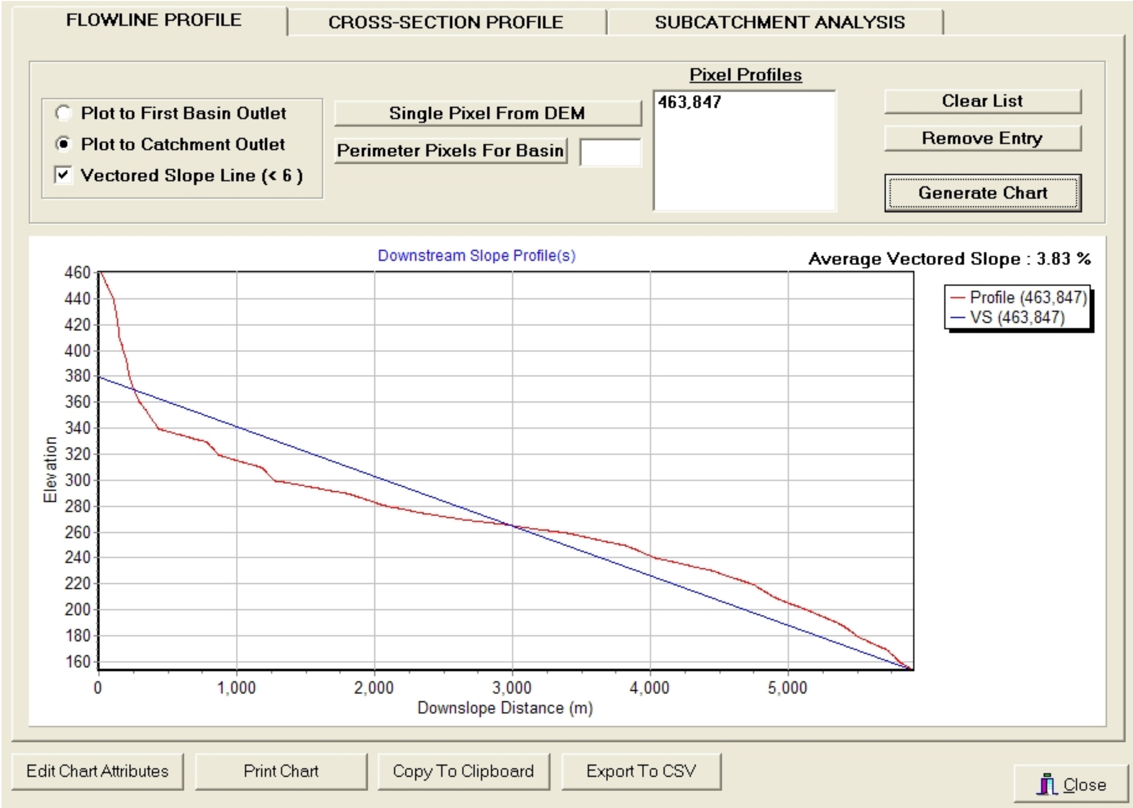


Figure 5-8 : Average Vectored Slope Downstream Profile

Figure 5-8 illustrates a downslope profile chart that has been generated for an individual cell (*row: 463, col: 847*). This chart illustrates the flow path profile from the cell to the major catchment outlet and the associated vectored slope. CatchmentSIM also overcomes the assumption relating to adoption of a single flow path as a representative slope profile for the subcatchment by allowing for a generalised average vectored slope calculation for the entire subcatchment. This is accommodated by the average of all average vectored slope profiles generated for every perimeter cell of the subcatchment. This value is called the Subcatchment Slope (%) and is listed in the Subcatchment Attributes form (*see page 162*).

Calculation of topographic parameters such as average vectored slopes for subcatchments are traditionally recognised as important for hydrologic analysis. However, CatchmentSIM enables further hydrologic analysis capabilities due to its improved flow routing algorithm. To demonstrate these techniques, the following sections will present a series of charts generated by CatchmentSIM to analyse the hydrologic properties of two sample subcatchments named **4.01** and **9.01** as shown in **Figure 5-9**.

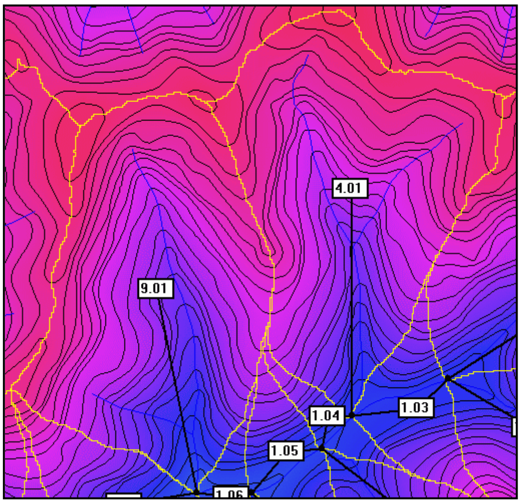


Figure 5-9 : Sample Subcatchments for Hydrologic Analysis Charts

These subcatchments are both upstream tributary subcatchments with a similar size and shape. Hence, they could be expected to have similar hydrologic properties. However, such an analysis is superficial and CatchmentSIM's hydrologic analysis tools can be used to assess the hydrologic properties of these subcatchments in greater detail and help quantify any differences in their hydrologic response.

5.4.2 Overland Flow Path Length Distributions

An important factor in the hydrologic response of a subcatchment lies in the frequency distribution of flow path lengths for a subcatchment. Furthermore, since water flows much faster in-stream than overland, it is important to analyse the overland flow path length characteristics of each subcatchment within a project. CatchmentSIM accommodates this type of analysis by generating charts such as that shown in **Figure 5-10**.

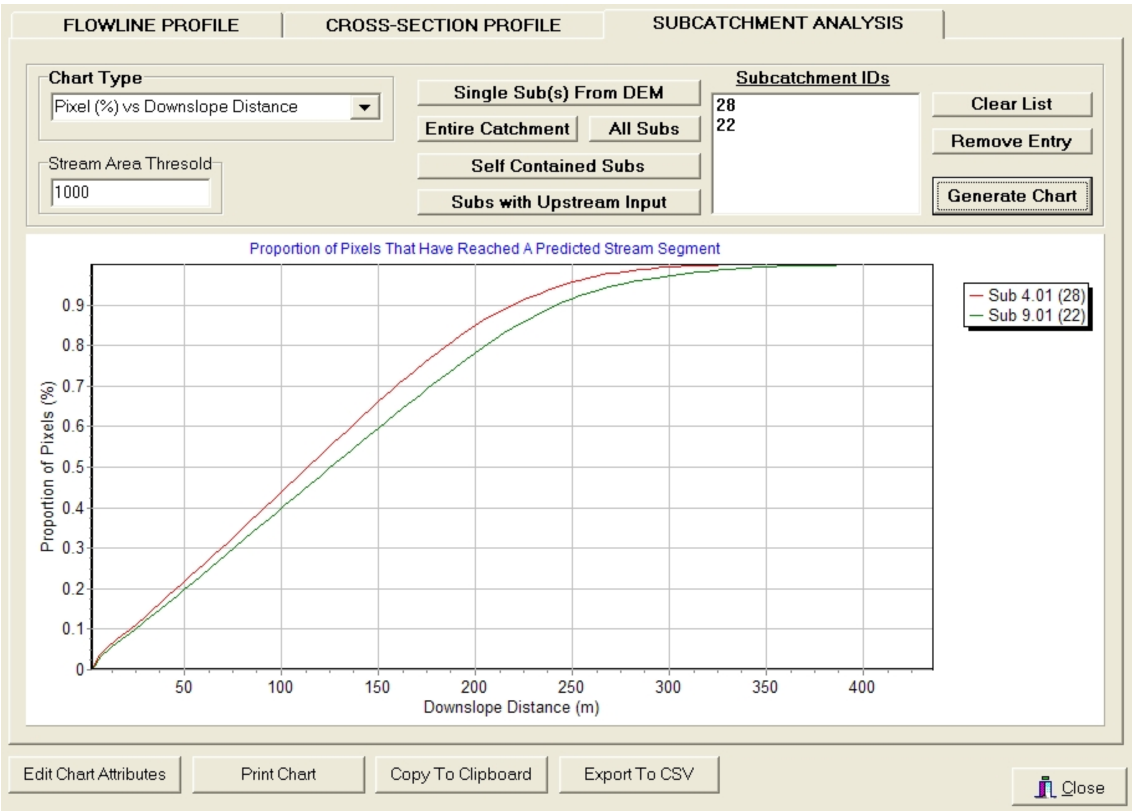


Figure 5-10 : Distribution of Cells w.r.t. Overland Travel Distance

The chart illustrated in **Figure 5-10** plots overland travel distance vs proportion of cells that have intersected the calculated stream network. It can be seen that the curve associated with subcatchment 9.01 is constantly to the right of the curve associated with subcatchment 4.01. For example, it takes approximately 10 metres more overland travel distance for flow paths from 50% of subcatchment cells to intersect a stream segment for subcatchment 9.01 as compared to subcatchment 4.01. This could indicate that subcatchment 9.01 has a slower hydrologic response to rainfall and should be assigned a longer (*slower*) lag coefficient in any subsequent hydrologic model.

5.4.3 Raster Drainage Density Distributions

A further hydrologic analysis technique is charting of raster drainage density versus Stream Area Threshold (SAT). This is a valuable tool because SAT is one of the chart axes, hence, the resulting chart is valid for a range of SAT values. This is in contrast to the chart illustrated in **Figure 5-10**, which is specific to an individual SAT, and will vary with the particular SAT adopted for generation of the stream network. An example of this chart is given in **Figure 5-11**, which analyses the aforementioned subcatchments.

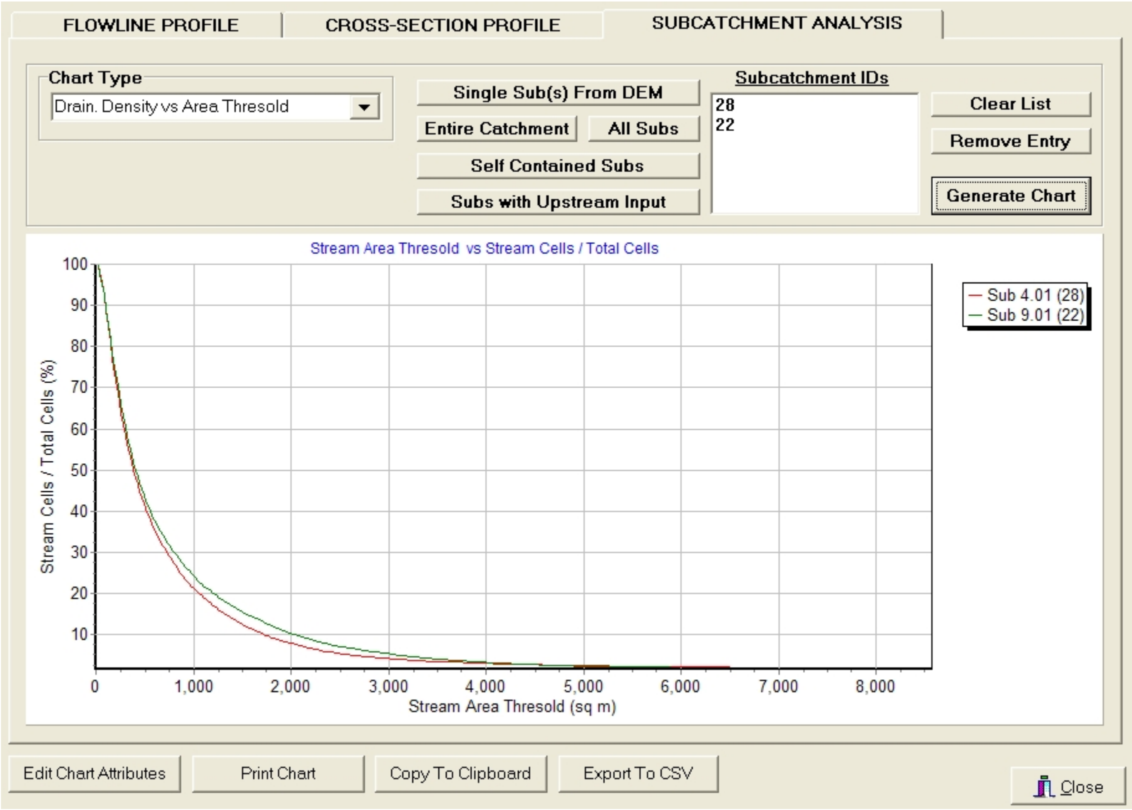


Figure 5-11 : Influence of Stream Area Threshold on Drainage Density

It can be seen in **Figure 5-11** that between SAT values of approximately 500 and 3500 the subcatchment curves deviate slightly. The curve associated with subcatchment 9.01 has a higher raster drainage density for a given SAT than the curve associated with subcatchment 4.01. This means that for this range of SAT values, subcatchment 9.01 has a higher proportion of cells with flow accumulation values greater than the SAT value. However, when analysed in the conjunction with the results illustrated in the previous chart, **Figure 5-10**, it is apparent that the spatial distribution of these stream cells is not as efficient since the overland flow lengths before stream cells are intersected are generally longer for subcatchment 9.01. Consequently, it can be established that the stream network associated with subcatchment 4.01 has more efficient space filling properties and may have a faster hydrologic response.

5.4.4 Horton Parameters

The hydrologic analysis enabled by Strahler / Horton ordering has been documented in Section 5.3.2 (*page 178*). However, some additional charting capabilities are available for analysis of Strahler / Horton stream networks. An important example of these charts is a log-log plot of the distribution of cumulative stream length for each Strahler / Horton order versus stream order as shown in **Figure 5-12**.

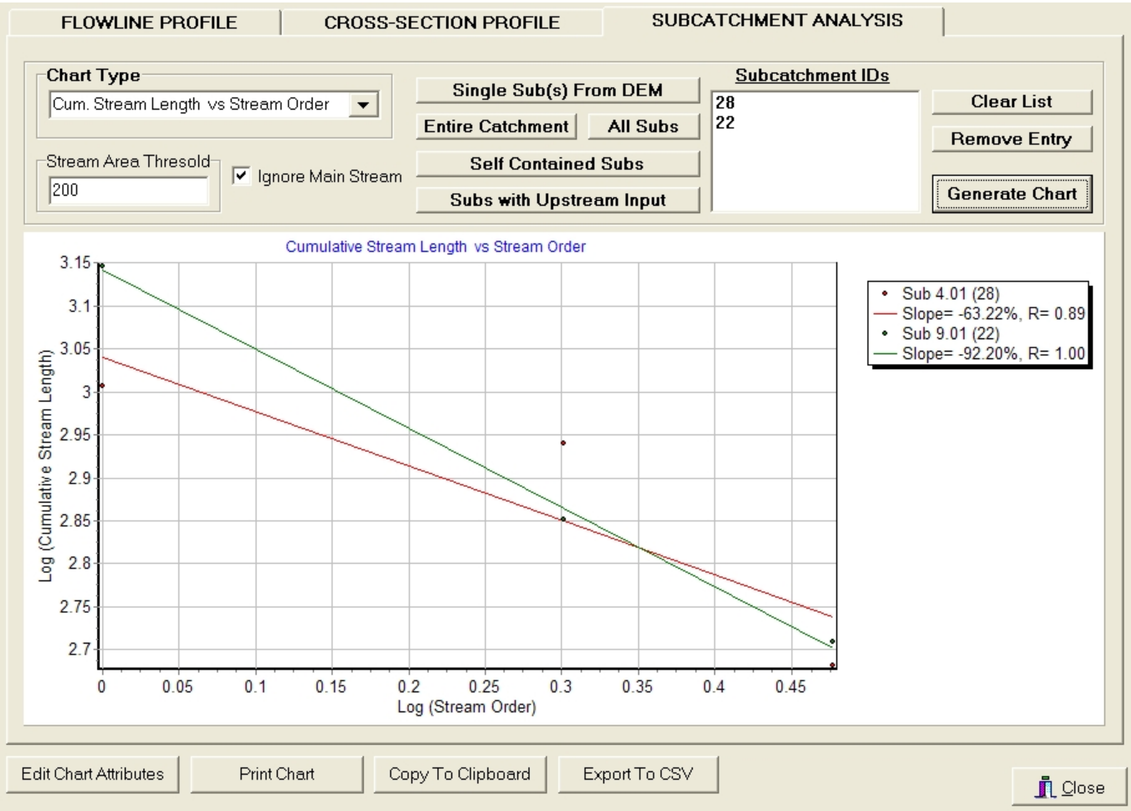


Figure 5-12 : Log-Log Plot of Cumulative Stream Length vs. Stream Order

Strahler (1957) found that a relationship also tends to exist between these variables although it is typically far less strong then the bifurcation relationship illustrated in **Figure 5-5** (*page 179*). However, differences between the gradient of the line of best fit derived from the log-log chart of cumulative stream length versus stream order can also be used to help assess the hydrologic characteristics of the subcatchments. In the case of the two sample subcatchments under analysis, this chart indicates that subcatchment 9.01 has a higher stream length in lower order streams than subcatchment 4.01. However, the fit between the line of best fit and the data points is too coarse to justify any significant conclusions in this case.

5.4.5 Hypsometric Curve

Strahler (1957) also introduced another type of topographic chart for use in geomorphological assessment called the hypsometric curve. This curve represents the relationship between relative height and relative area as shown in **Figure 5-13**.

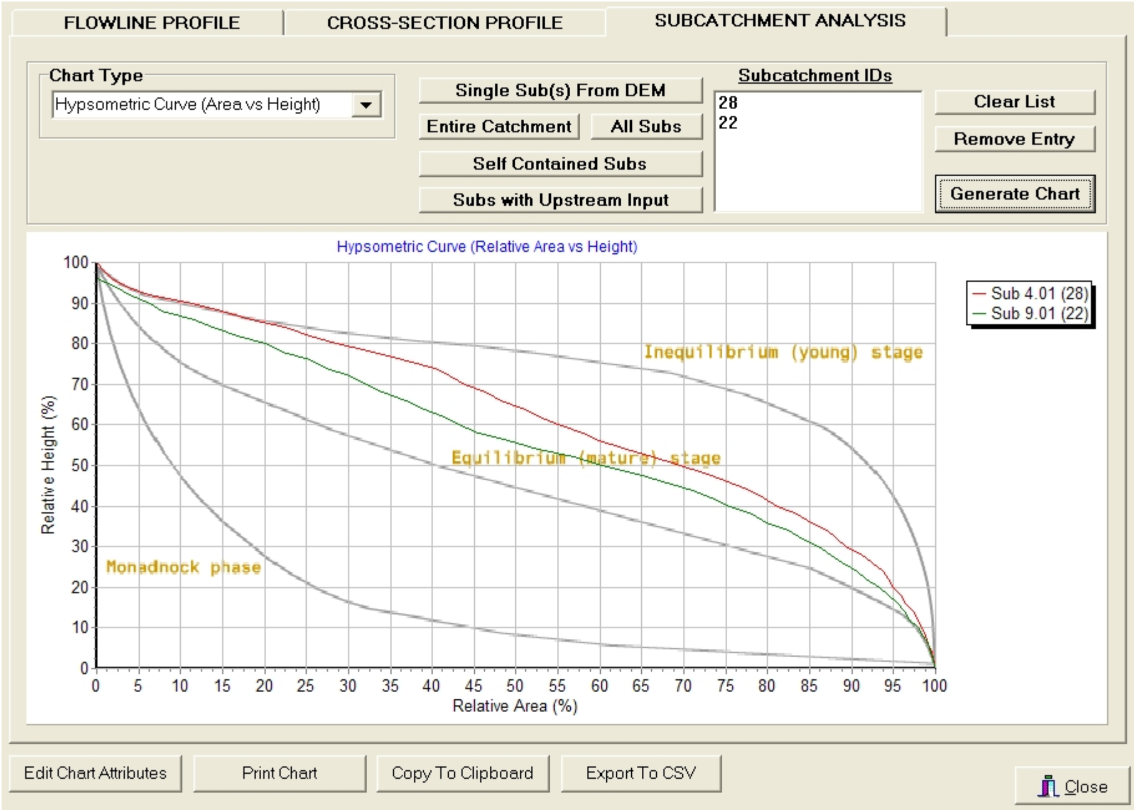


Figure 5-13 : Hypsometric Curve

As illustrated in **Figure 5-13**, CatchmentSIM allows the resulting curve(s) to be assessed against a background image (Strahler 1957) to determine what phase of the catchment or subcatchment's geomorphologic life it is in. However, this chart can also be used to assess the subcatchment slope and drainage characteristics. With respect to the subcatchments under analysis, subcatchment 4.01 appears to have shallower slopes in the upper subcatchment areas and steeper slopes in the lower subcatchment areas, in comparison to subcatchment 9.01. Thus, subcatchment 4.01 has a steeper slope than subcatchment 9.01 for a larger proportion of the relative area (*the final 60% of relative area, 40% - 100% on bottom axis*). This is further evidence for a faster rainfall response in subcatchment 4.01 than subcatchment 9.01.

5.4.6 Summary of Hydrologic Analysis Tools

This section has presented a demonstration of how CatchmentSIM's hydrologic analysis tools can be used to quantitatively investigate the hydrologic properties of a catchment and its subcatchments. The sample subcatchments presented in this analysis were of very similar size and shape. Furthermore, due to their proximity to each other, they could be assumed to share common geomorphological and hydrologic characteristics. However, even in these circumstances, the hydrological analysis algorithms embodied within CatchmentSIM were able to quantify genuine deviation in the hydrologic characteristics of these subcatchments. These deviations could be used to better define lag coefficients in any hydrologic or hydraulic modelling software that may be coupled with CatchmentSIM.

5.5 CONCLUSION

This chapter documents an analysis comparing CatchmentSIM's flow routing algorithm with the D8 method, which is utilised by almost all available software products. CatchmentSIM's flow routing algorithm was shown to produce more accurate results than the D8 method in terms of both flow path mapping and subcatchment boundary delineation.

Furthermore, this chapter has aimed to demonstrate the ability of CatchmentSIM's hydrologic analysis algorithms to aid users to quantify the hydrologic characteristics of a catchment, its subcatchments and even individual DEM cells. The potential of these tools is greatly enhanced due to CatchmentSIM's improved flow routing algorithm, which enables calculation of accurate flow path length calculations that are not possible with single or multiple direction raster flow routing algorithms. This in turn allows calculation of a number of parameters and charts to help quantify the hydrologic properties of subcatchments, including flow path length frequency distributions. Furthermore, the ability to assess the geomorphologic suitability of calculated stream networks and assess its fractal statistics can provide direct assistance for assignment of lag parameters in subsequent hydrologic or hydraulic modelling packages.

Chapter 6 will present two case studies illustrating the advantages of CatchmentSIM's algorithms in comparison to current techniques, as well as the capabilities of CatchmentSIM's algorithms to be applied in urban areas.

6 CASE STUDIES AND APPLICATIONS

6.1 INTRODUCTION

During this research project CatchmentSIM was developed from scratch as a stand-alone windows application written in Delphi. The first version of CatchmentSIM was made available on the project website (http://www.uow.edu.au/~cjr03) in July of 2002. Since this time 14 new versions of CatchmentSIM have been released with many new features and software bugs removed. As of the 31st December 2003, the website had received over 37,000 hits and 557 users had registered on the member database in order to download the software. 325 of these users subsequently progressed to install and use the software. The website hits, membership sign-ups and recorded software registrations are illustrated in **Figure 6-1**. The membership database of CatchmentSIM users is listed in **Appendix D**.

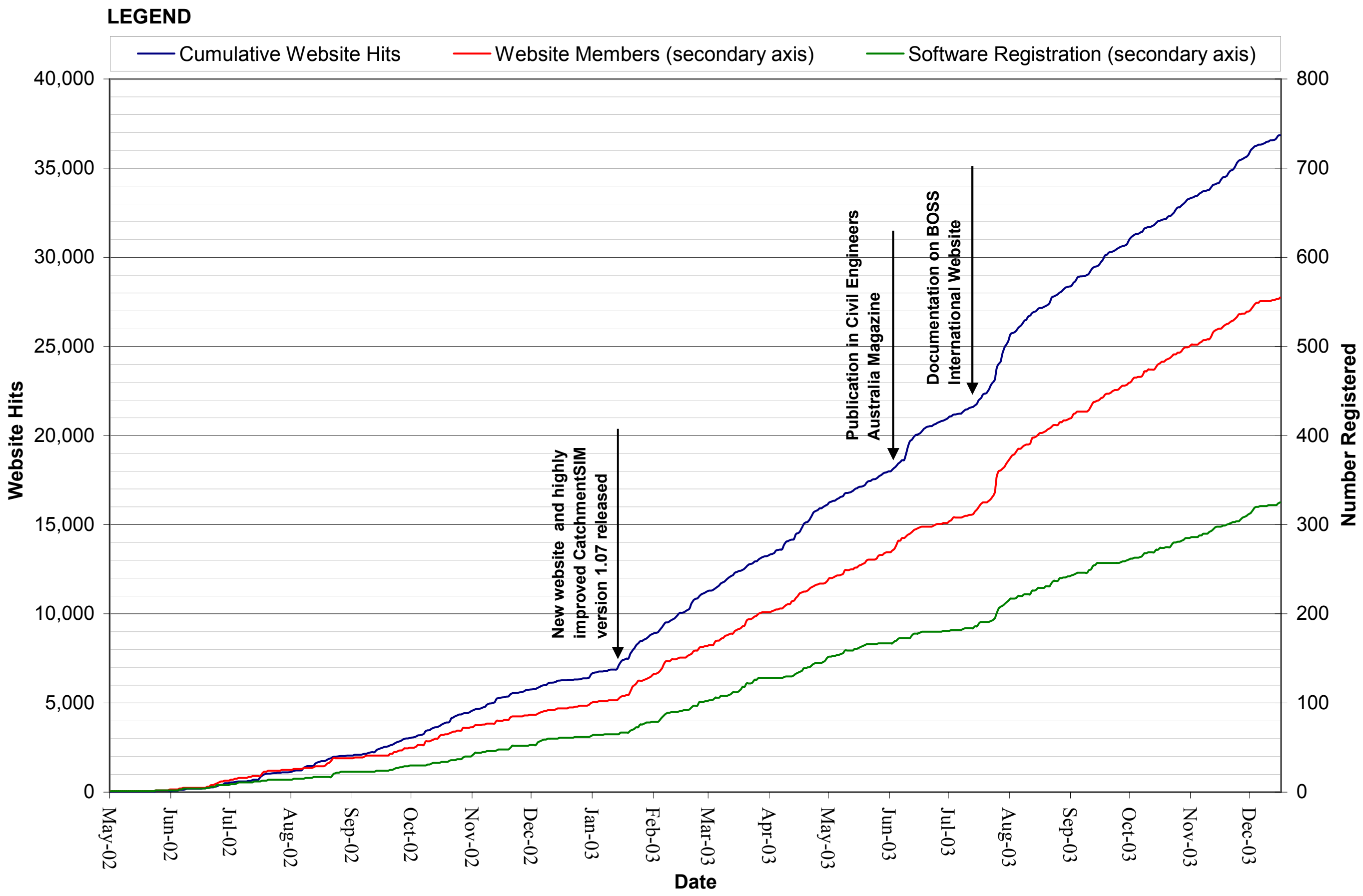


Figure 6-1 : CatchmentSIM Web Traffic and Membership Database

As outlined in Section 2.10 (*page 78*), a significant barrier to coupling of GIS and hydrologic models is the largely country specific approaches to hydrologic modelling. For example, the rainfall runoff models endorsed for use in Australia by the standard industry resource, Australian Rainfall and Runoff (Pilgrim 1987) are RAFTS-XP WBNM and RORB. These models are not applied in many other countries except in some areas of south-eastern Asia. A fundamental goal of the development of CatchmentSIM was to facilitate more accurate hydrologic modelling in a wide range of countries using a wide range of available hydrologic models. The flexibility and ease of coupling provided by the CSTalk macro language (*see page 165*) was a core tool for realisation of this goal. The spatial distribution of CatchmentSIM users is a good measure of the success of CatchmentSIM in meeting this goal. As of the 31st December 2003, CatchmentSIM had members in 61 different countries. A thematic map illustrating the spatial distribution of CatchmentSIM members is shown in **Figure 6-2**.

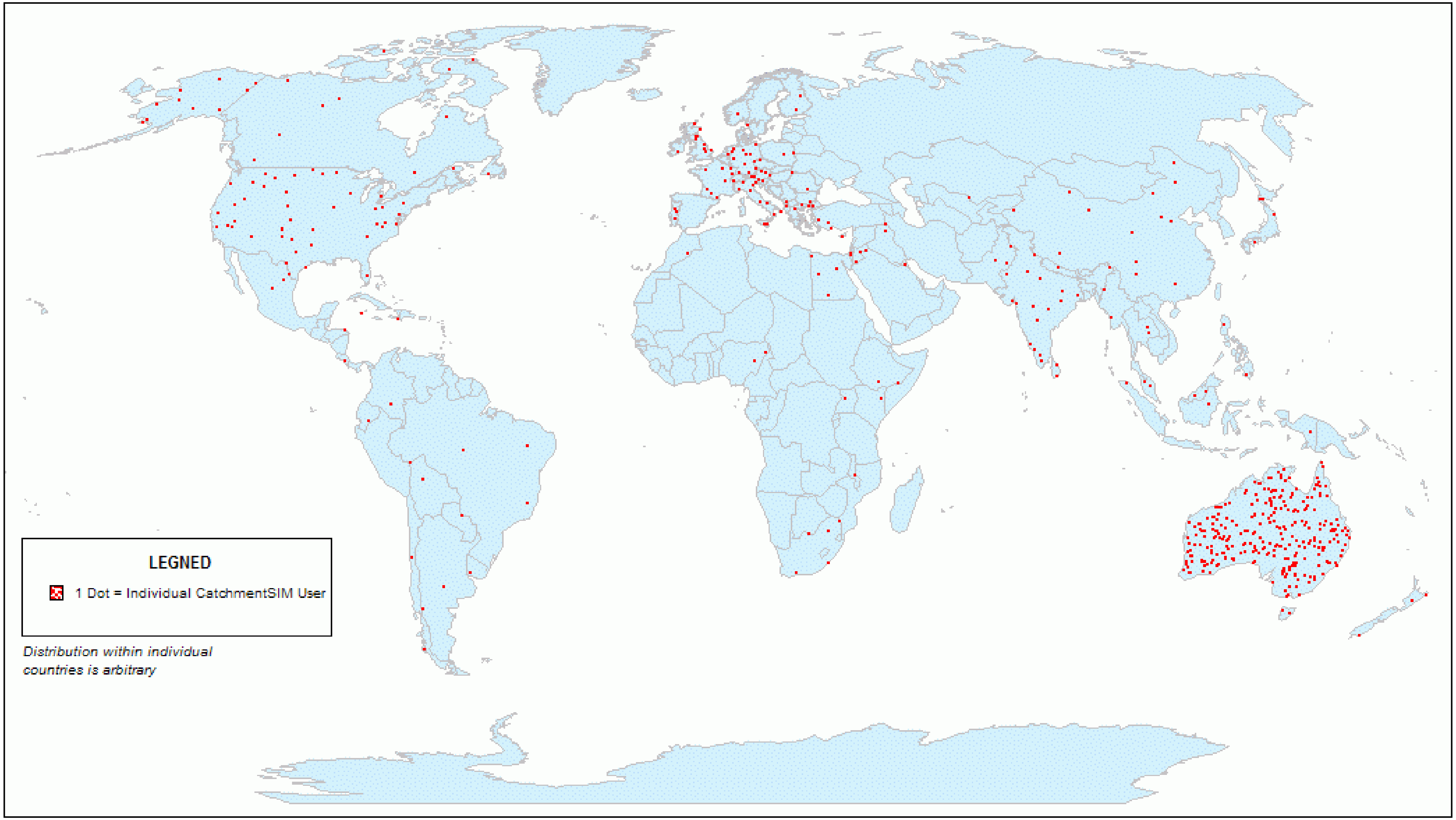


Figure 6-2 : Spatial Distribution of CatchmentSIM Users

CatchmentSIM users have applied the software to projects with a wide variety of objectives in a wide variety of geographic regions. A sample of these projects are:

- Development of flood forecasting systems in the Three Gorges Dam catchment (*Min Yaowu, Changjiang, China Water Resources Commission*).
- Processing of up to 300 Local Stormwater Management Plans (LSMPs) by Brisbane City Council (BCC), Australia (*Mike Bardsley and Don Carroll, BCC*). Other Australian councils are currently undertaking verification test and may also use CatchmentSIM for LSMP revision.
- Recalculation of Queensland flood study results with CatchmentSIM coupled with URBS by the Bureau of Meteorology (BOM) in Brisbane, Australia (*Terry Malone and David Stephens, BOM*).
- Modelling catchment erosion-reservoir siltation processes in Ethiopian catchments (*Lulseged Tamene, University of Bonn, Germany*).

Most of the work being undertaken with CatchmentSIM was still underway at the time of writing this thesis, however some projects had been completed. Two of these projects provide excellent practical demonstrations of the advantages of the unique CatchmentSIM algorithms and will be documented in the following sections. These are a small sample of the work undertaken by CatchmentSIM and other case-studies can not be presented due to space restrictions. The reader is advised to check the project website for additional case studies.

6.2 HOLLAND PARK LOCAL STORMWATER MANAGEMENT PLAN

This project was undertaken by Michael Bardsley from City Design, Brisbane Australia. Brisbane City Council (BCC) commissioned City Design to undertake a Local Stormwater Management Plan Technical Report (LSMPTR) for the 270 hectare Holland Park catchment in Brisbane, Australia. The LSMPTR is aimed to alleviate and minimise flooding problems experienced in the Holland Park vicinity. The LSMPTR including the analysis undertaken with CatchmentSIM has been developed into a report (*currently in draft*) entitled "Holland Park Local Stormwater Management Plan" City Design Pty Ltd Prepared for Waterways Program, Urban Management Division, Brisbane City Council.

One of the key criteria within the study was to "*identify and assess stormwater and flooding impacts on the Holland Park catchment*". This was to be achieved by application of a range of hydrologic and hydraulic stormwater modelling packages. This project was seen as a trial of suitable techniques to form the basis for a further 200-300 LSMPs with the Local Government Area (LGA) of Brisbane City Council. As such, City Design was eager to investigate new GIS approaches to improve accuracy and save time.

In order to develop a computer model of the Holland Park stormwater system in the DRAINS (Watercom Pty Ltd 1998) software package it was necessary to generate subcatchment boundaries, areas and generalised topographic parameters for the subcatchments draining to every stormwater pit in the catchment. Delineation of this quantity of subcatchments using existing techniques of hand delineation of subcatchment boundaries over topographic maps was seen as too time consuming and error prone. Consequently, faster and more accurate GIS approaches were sought. However, any automated GIS approach would need to take account of the highly urbanised nature of the catchment. CatchmentSIM was one of the products trialled on this project as described in the following methodology.

6.2.1 Project Methodology

The project consisted of importing an external DEM developed from aerial survey into CatchmentSIM and using internal algorithms to remove all flats and pits from the DEM. The road crown database in the area was represented in the DEM by a 'road burning' approach. Inlet gullies were directly imported from a GIS database and subcatchment boundaries and parameters were automatically calculated prior to export of catchment and subcatchment characteristics to the DRAINS model. The DEM, imported road network and inlet gullies are shown in **Figure 6-3**.

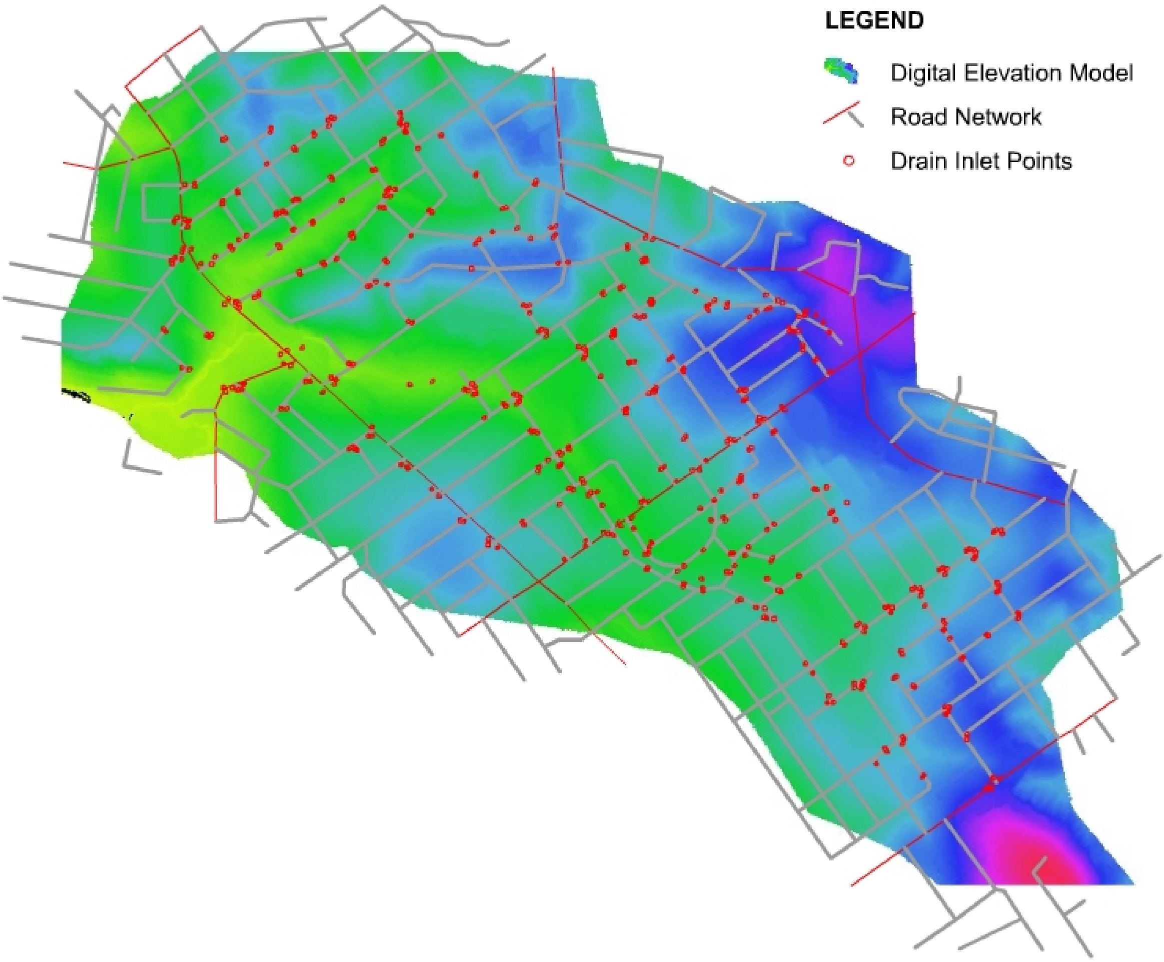


Figure 6-3 : Holland Park GIS Layers

The DEM shown in **Figure 6-3** was originally developed by aerial photogrammetry and was a highly complex TIN of several million points. This was converted to a raster DEM with the 12D geo-processing software, since this project was completed before CatchmentSIM included the functionality for sampling TIN models. The DEM resolution was 2499 rows by 3249 columns, which forms a DEM with over 8 million cells.

Flat and pit cells within the DEM were treated by the PFS algorithm until flow could be processed from all points within the catchment.

The key challenge in modelling the Holland Park environment lies in the highly urbanised nature of the catchment. Most of the topographic features that will control flow in the area are not represented in surveyed GIS data (*even highly accurate aerial photogrammetry based survey*). The single most important urban features in the area are the roads. Consequently, it was crucial that these were adequately represented in the DEM. As outlined in Section 4.10 (*page 155*), CatchmentSIM provides two different approaches for representation of urban features in projects, hard-coding of these features into the DEM, or simulation of these features as overriding external controls. For this project, the road network was hard-coded into the DEM. This was achieved using CatchmentSIM’s vector data set operations to raise all DEM cells underlying road crown alignments by 0.5 metres.

Following the 'road burning' the PFS algorithm was applied to treat all flat and pit cells that were formed during the ‘road burning’ procedure. This caused the roads to be breached by major drainage paths at their points of lowest elevation. This may be seen by looking closely at the CatchmentSIM generated minor drainage network displayed in **Figure 6-5** (*page 204*).

The subcatchment inlets were derived based on the Asset Database of Brisbane City Council representing inlet gullies. 466 inlets from this database were directly imported into CatchmentSIM.

Following import of the subcatchment outlets, flow routing was undertaken for the entire catchment producing the subcatchment boundaries shown in **Figure 6-4**.

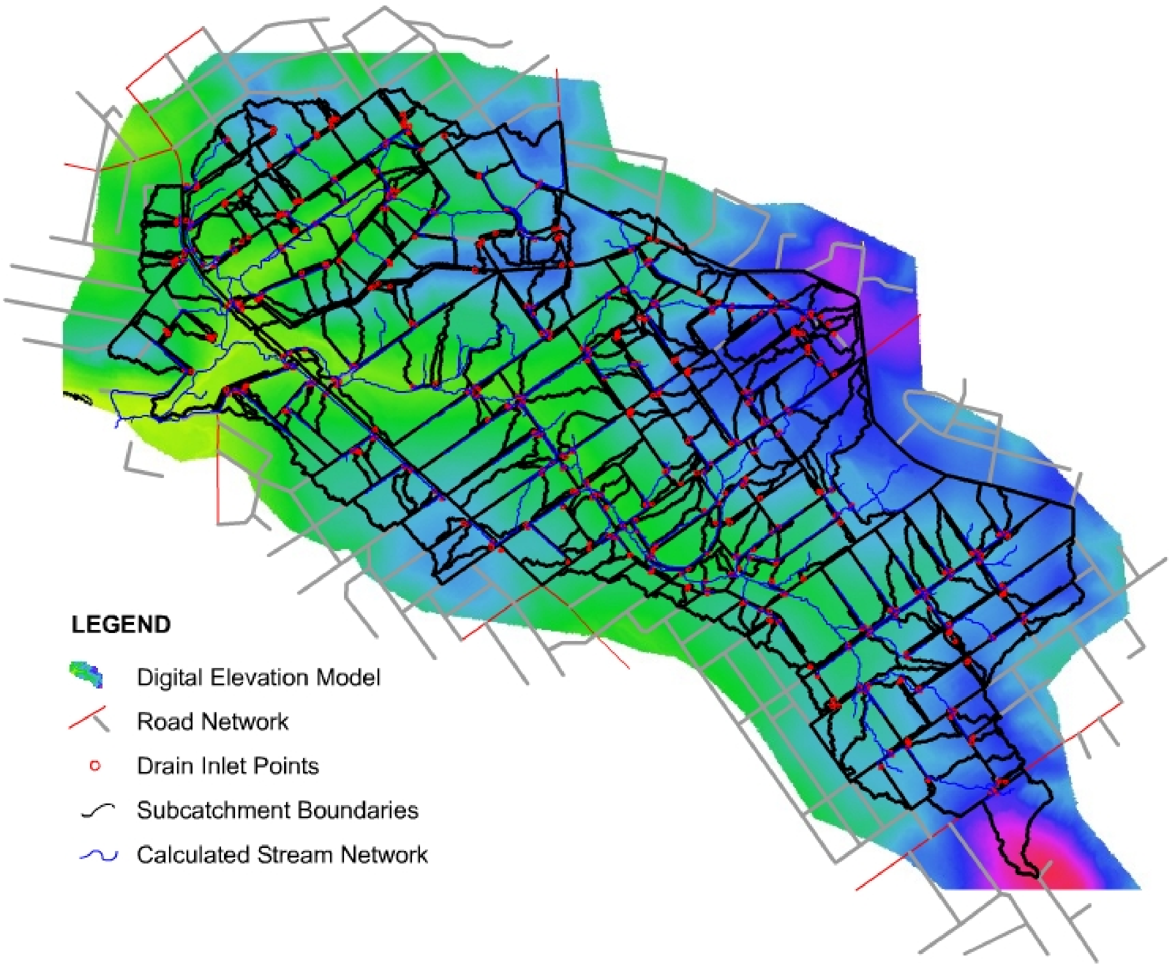


Figure 6-4 : Holland Park CatchmentSIM Results

The level of detail that is accommodated by the CatchmentSIM flow routing algorithm and resultant modelling of urban features can be clearly seen by examining the CatchmentSIM results superimposed over aerial photography. **Figure 6-5** illustrates the subcatchment boundaries, road crown alignments, inlet gullies and calculated minor drainage paths for the project (*a vector stream network calculated at a low SAT value*).

Figure 6-5 : Holland Park Results Superimposed over Aerial Photography

It can be seen in **Figure 6-5**, that the road crown alignments strongly influence the subcatchment boundaries and minor drainage paths, yet in other areas the flow is controlled by the DEM. This has allowed for realistic flow paths and inlet gully drainage areas to be calculated by combination of a sampled DEM with an urban features (*road crown*) database.

The Brisbane City Council City Plan GIS database was also imported into CatchmentSIM to help represent the urban environment. This database was imported as a CatchmentSIM impervious areas database in order to calculate impervious proportions for each inlet gulley drainage area. This GIS layer may be seen in **Figure 6-6**. The different colours represent different land-use types and different impervious proportions were assigned to these polygons to realistically represent their varying degrees of imperviousness.

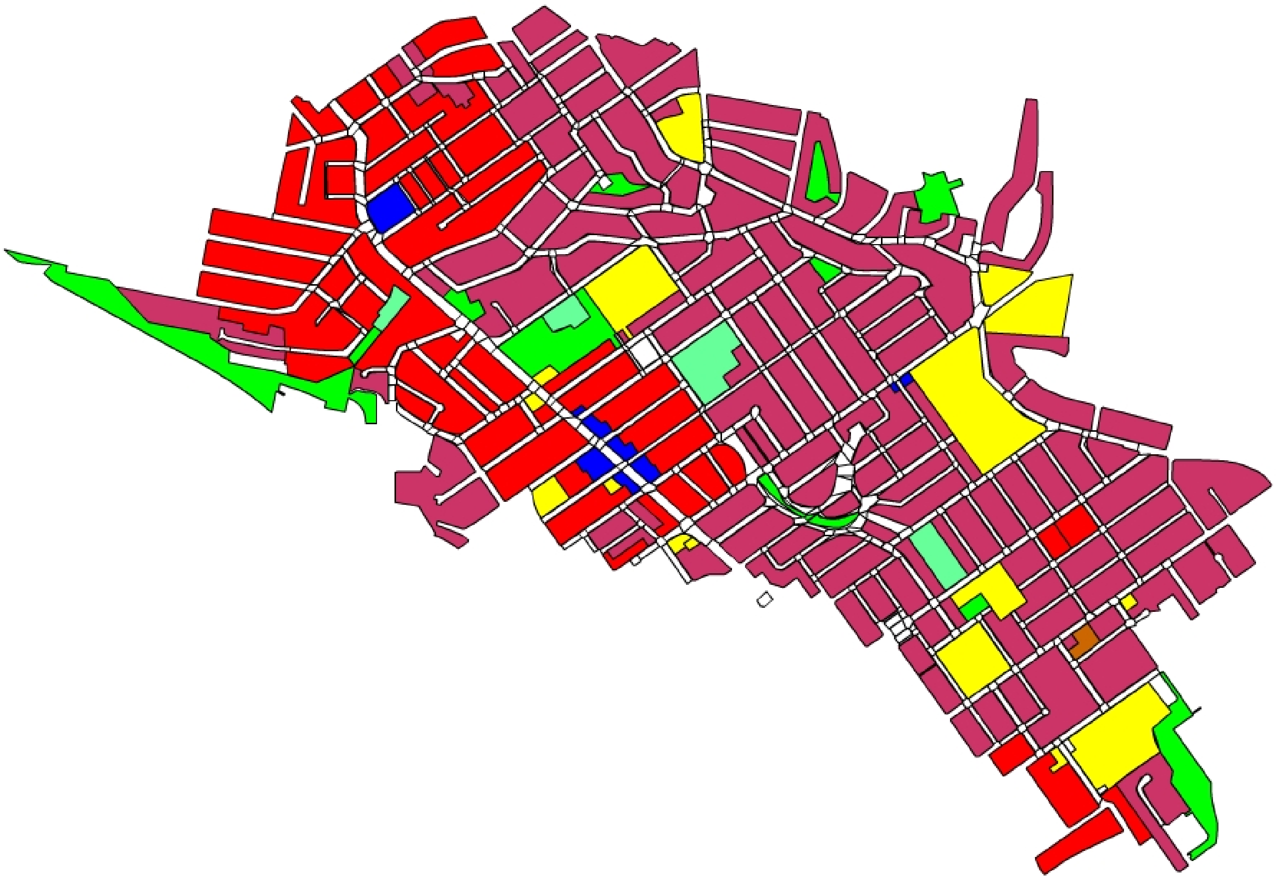


Figure 6-6 : Holland Park City Plan GIS Database

Following assignment of impervious proportions to each inlet gulley drainage area, the project was exported to the hydrologic / hydraulic DRAINS model. This was achieved by exporting CatchmentSIM data to a CSV file and then using DRAINS spreadsheet functions to import subcatchment attributes. CatchmentSIM now includes a CSTalk macro script designed for simpler coupling with the DRAINS model.

6.2.2 CatchmentSIM Contribution

This project would not have been possible without CatchmentSIM's vector data set operations tools (*for raising road crown alignments*) or the PFS algorithm for treatment of resultant flat and pit cells within the DEM. Raising DEM cells underlying the road crown alignments creates large closed depressions bounded by road crowns. Application of traditional filling algorithms and the J&D Algorithm (*see page 44*) would have simply filled the closed depression forfeiting any benefits associated with the exercise. The PFS algorithm is crucial to the success of this project because it finds the least cost path at which to breach road crowns as shown in **Figure 6-5**. As a result of the requirement for these advanced algorithms, this project could not have been completed as successfully in any of the available products reviewed in Section 2.11 (*page 84*).

6.2.3 User Comments on this Project

Feedback received from City Design following completion of this project was very positive. City Design found that CatchmentSIM was very successful at delineating the subcatchment boundaries in the highly urbanised Holland Park catchment. They maintain that the level of detail in the representation of overland flow behaviour is excellent and is the result of the use of CatchmentSIM in combination with excellent accuracy laser survey data.

When comparing CatchmentSIM to alternative products, they found that CatchmentSIM produced better results than either MapInfo Vertical Mapper or ESRI 3D Spatial

Analyst. The major advantages aside from improved representation of urban flow behaviour were more flexibility in the manipulation of data (pre-processing) and software integration.

City Design reported that using CatchmentSIM on this project saved large quantities of time and money and they intend to apply the software to future LSMPs in Brisbane.

6.3 UPPER WASHITA CATCHMENT EDNA COMPARISON

6.3.1 Introduction

This project was undertaken by the author to verify CatchmentSIM's algorithms against the geo-processing undertaken by the United States Geological Survey (USGS) during their on-going project called Elevation Derivatives for National Applications (EDNA). The EDNA project utilises the existing National Elevation Dataset (NED) (*a raster DEM data set*), and the National Hydrography Dataset (NHD) (*a vector watercourse alignment data set*) in combination with automated hydrologic DEM analysis algorithms to produce the following derivative data sets:

- Aspect
- Contours
- Filled DEM
- Flow Accumulation
- Flow Direction
- Reach Catchment Seedpoints

- Reach Catchments
- Shaded Relief
- Sinks
- Slope
- Synthetic Streamlines

This project is the most comprehensive automated terrain analysis work currently being undertaken in the world. A sample data set is available on the EDNA website (http://edna.usgs.gov/Edna) for the 835,000 hectare Upper Washita catchment in the Arkansas-White-Red River Basin. This data has been made available as a sample of a complete EDNA analysis and to provide a "*testing ground for new and improved methods and tools*".

As such the source data sets were downloaded and imported into CatchmentSIM to enable comparison of CatchmentSIM with the various algorithms used to compile the EDNA data sets.

6.3.2 Project Methodology

The Upper Washita NED DEM in raw format was imported into CatchmentSIM with 4475 rows and 5187 columns. The NHD watercourse alignments were imported into CatchmentSIM and the 'Interpolate Streams over Existing DEM' tool was applied. This algorithm is similar to the watercourse integration algorithm documented in Section 4.4.2 (*page 122*) but it is designed for application to sampled DEMs as opposed to those in the process of being interpolated. The algorithm processes the watercourse alignment network to assign flow directions and then ensures that DEM cell elevations underlying the watercourse alignments decrease in a downstream direction. Where cell elevations are flat or increase in a downstream direction, the algorithm continues to process the watercourse alignment until a cell of lower elevation is found. Then all cells between these points are assigned linearly interpolated elevations along the watercourse alignment.

Following this the filling algorithm was applied to treat some hill-crest areas where the limited vertical precision of the DEM had flattened the hill-crest. Finally, the PFS algorithm was applied to remove all remaining flat and pit cells. Catchment and subcatchment delineation was then processed based on the outlet points identified in the EDNA database. This yielded a subcatchment network that is very similar to the ENDA results and is shown **in Figure 6-7**.

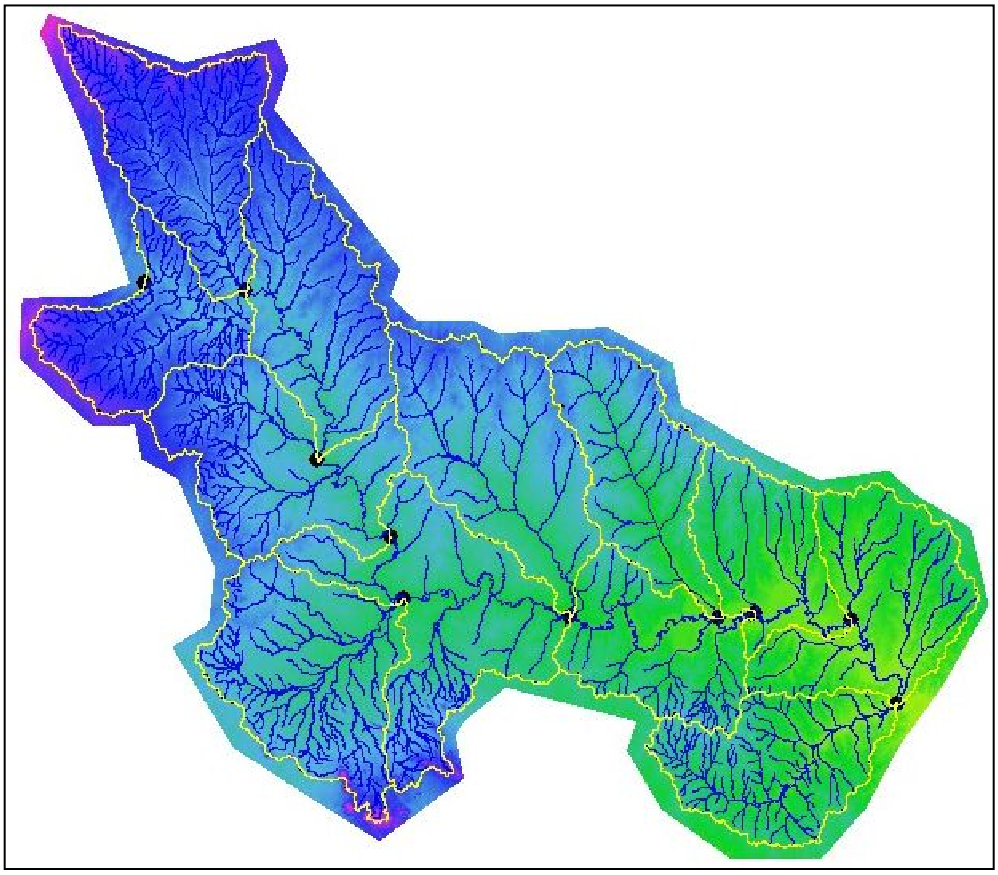


Figure 6-7 : Upper Washita CatchmentSIM Results

A 3D representation of the Upper Washita catchment boundary and calculated vector stream network derived by CatchmentSIM can be seen in **Figure 6-8**.

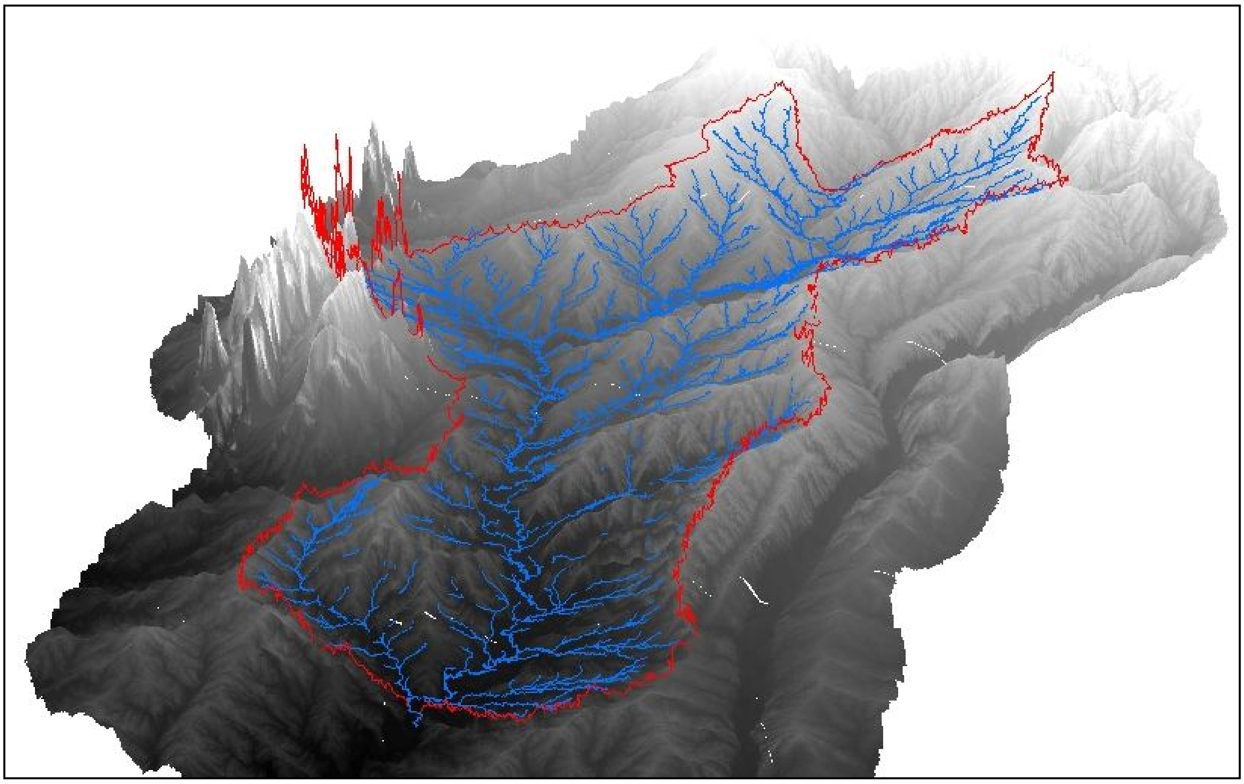


Figure 6-8 : Upper Washita 3D CatchmentSIM Catchment and Streams

The results generated by CatchmentSIM can be compared to those derived by the EDNA algorithms, which use the Arc Hydro tools within the ArcGIS framework as documented in Section 2.11.1 (*page 85*).

6.3.3 Catchment Delineation Comparison

The catchment boundaries generated by CatchmentSIM and the D8 algorithm were closely matching in most regions. However, some areas of discrepancy were found. These were not due to the flow routing algorithm, rather, were a consequence of the differing approaches to treatment of flat and pit cells. A sample area of catchment boundary delineation differences is shown in **Figure 6-9**.

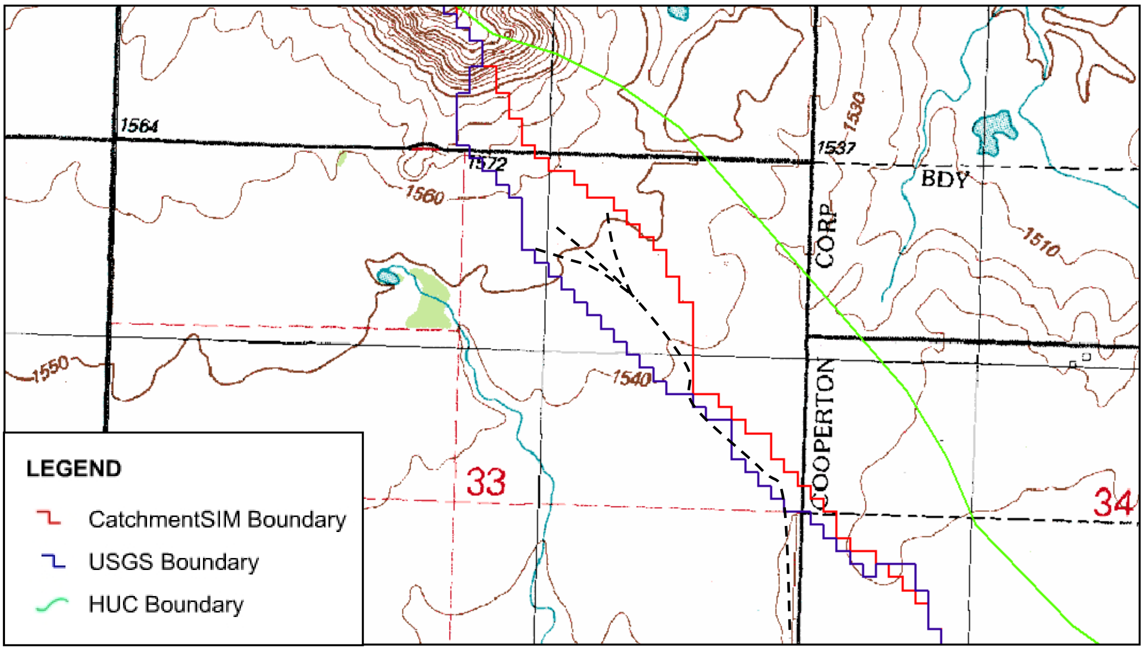


Figure 6-9 : Upper Washita Catchment Delineation Differences

As shown in **Figure 6-9**, the CatchmentSIM and EDNA derivations of the catchment boundary differ slightly. However, both of the automated catchment boundaries are more accurate than the Hydrologic Unit Catalog (HUC) boundary which had previously been done by hand. It is not entirely clear from the contours, which of the automated catchment boundaries is more correct. However, it can be argued that the CatchmentSIM boundary is more correct because the dashed black lines are realistic flow paths derived from the contours which breach the USGS derived boundary.

Other regions of catchment delineation deviation between the two approaches are shown draped over the 3D surface of the original NED DEM in **Figure 6-10**.

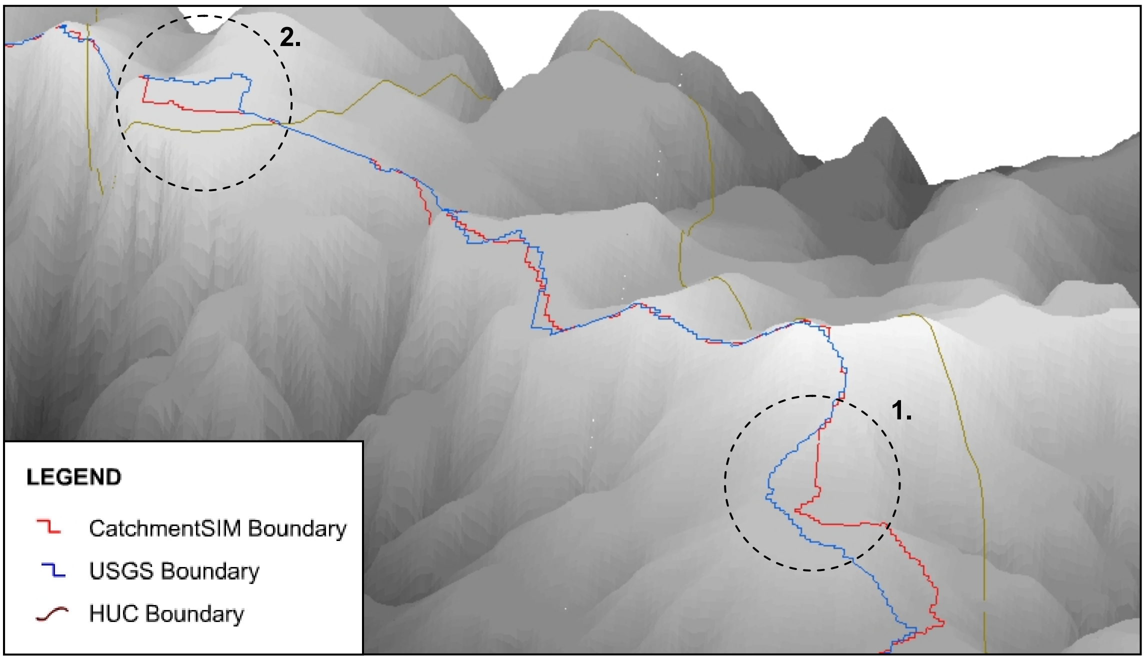


Figure 6-10 : Upper Washita Catchment Delineation Differences (3D)

Similarly to **Figure 6-9**, it can be seen in **Figure 6-10** that both automated approaches are more accurate than the hand delineated HUC catchment boundary. The observed differences in the automated catchment delineation in **Figure 6-10** are due to the use of the PFS algorithm as opposed to the J&D algorithm for treatment of flat and pit regions. A quantitative judgement of which boundary is correct is difficult, however, it can be seen that the CatchmentSIM algorithms produce a catchment boundary that is more able to identify ridge lines in areas of low sampling definition (*Circle 1*) and is better able to bisect flat hill-crest areas (*Circle 2*).

The differences between the flow routing algorithms adopted in the USGS approach (*D8 method*) and CatchmentSIM's flow routing algorithm are more pronounced in areas near catchment outlets as outlined in Section 5.2 (*page 172*). An example of the subcatchment boundaries generated near the outlet of one of the Upper Washita subcatchments can be seen in **Figure 6-11**.

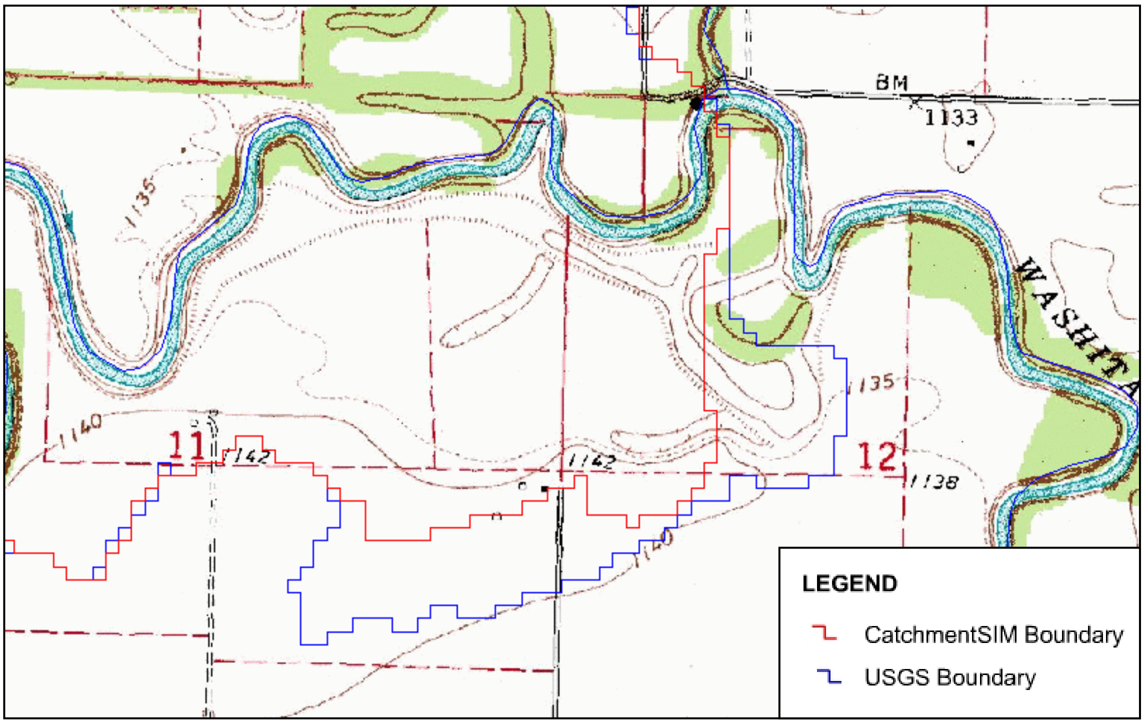


Figure 6-11 : Subcatchment Delineation near Outlets

It can be seen in **Figure 6-11** that the CatchmentSIM boundary is more successful at identifying the expected ridge line between the 1140 contour alignment towards the bottom the figure.

6.3.4 Stream Network Comparison

CatchmentSIM also produced a very different stream network than the USGS approach even when using the same SAT value for channel head identification. The USGS selected a SAT value of 5,000 cells (*4.5* km^2) for deriving a calculated stream network based on matching the NHD data set used to condition the DEM. **Figure 6-12** illustrates the NHD, EDNA and CatchmentSIM vector stream network generated at the same SAT value.

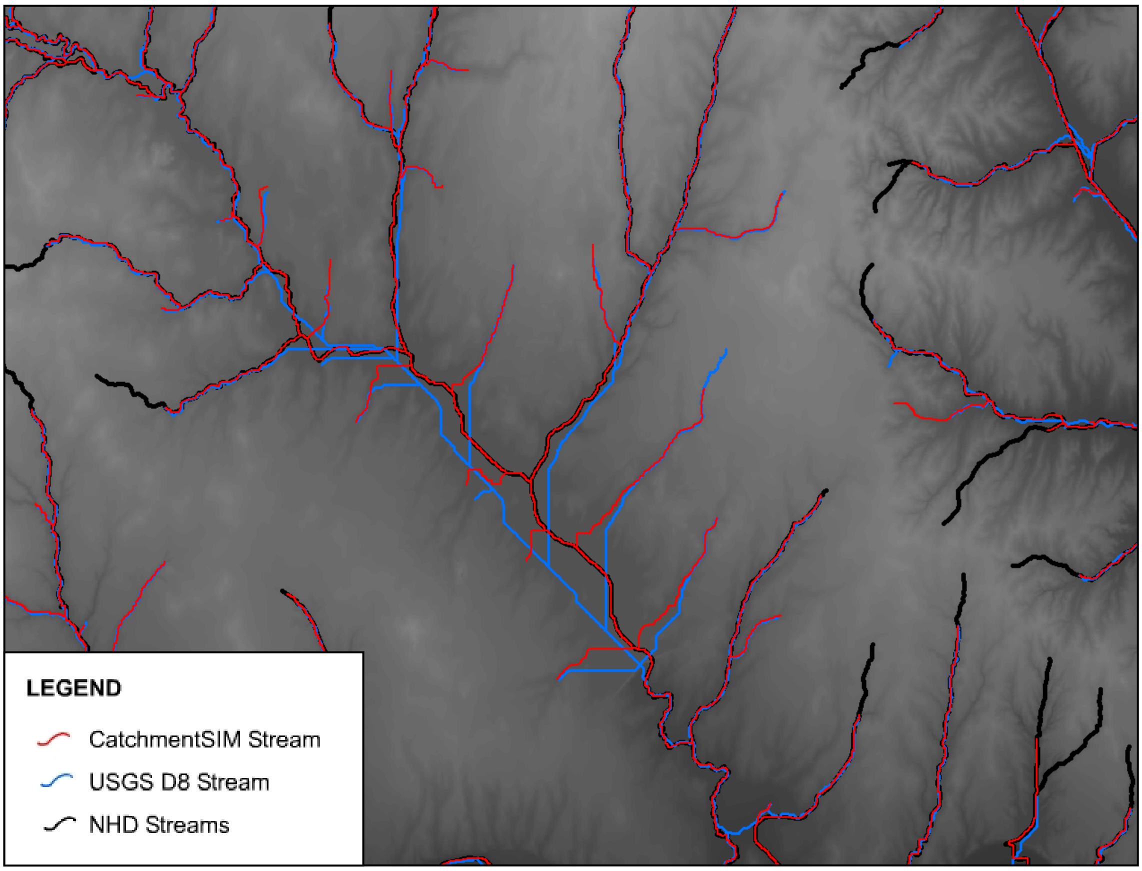


Figure 6-12 : Upper Washita Stream Network Comparison over DEM

It can be seen in **Figure 6-12** that the CatchmentSIM stream network is better able to match the NHD stream network and does not exhibit the 8 direction angular bias that is commonly associated with the D8 method and evident in the centre section of the figure.

To investigate the effect of increasing the detail level of the calculated stream networks, the SAT was lowered to 200 cells (*0.18 km*^{2}) to examine the ability of the software products to represent minor drainage paths and to test the effectiveness of the flow routing algorithm. **Figure 6-13** illustrates a comparison of these stream network over the 1:24,000 Digital Raster Graphic (DRG) mapping supplied by the USGS.

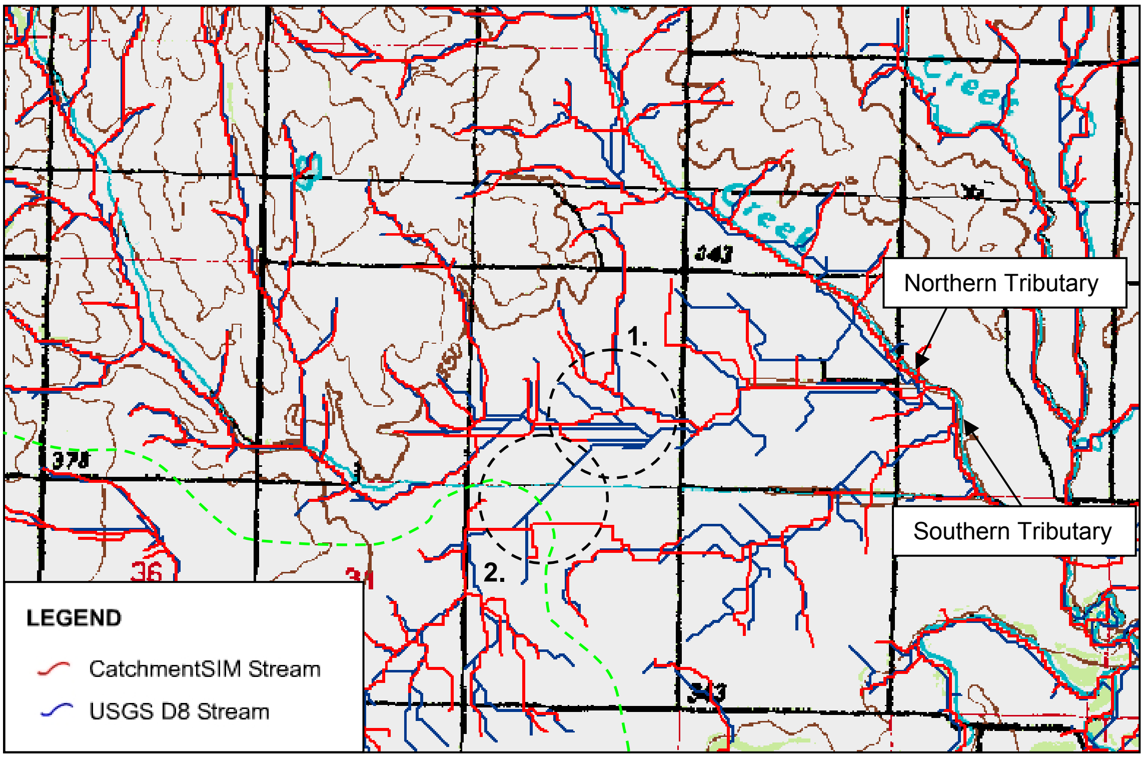


Figure 6-13 : Upper Washita Stream Network Comparison

The parallel flow paths associated with the J&D algorithm and the D8 method are clearly evident in the USGS D8 generated stream network as shown in **Figure 6-13**

(*Circle 1*). The CatchmentSIM network has a more realistic fractal nature due to the PFS flat and pit cell treatment algorithm and the more advanced CatchmentSIM flow routing algorithm.

Furthermore, the increased resolution of the vector stream networks has revealed a significant deviation in the two networks (*Circle 2*). The USGS model incorporates the drainage area in the bottom left of the figure (*green dashed line*) to the northern tributary while the CatchmentSIM model indicates this area draining to the southern tributary input. Thus, if subcatchments were generated for these two tributaries, the two models would produce very different results. It is not entirely clear from the DRG mapping which model is correct since there are no contours in the vicinity. However, the significance of this deviation is that the different hydrologic conditioning and flow routing algorithms can have major impacts on subcatchment delineation and stream network generation.

6.4 CONCLUSIONS

These two case studies profiling research that has been completed with CatchmentSIM, aim to demonstrate the capabilities of CatchmentSIM and the algorithms it employs. The Holland Park Local Stormwater Management Plan project demonstrates how the hard-coding of urban structures in conjunction with CatchmentSIM's improved PFS flat and pit removal algorithm can accommodate accurate modelling of urban features that may have otherwise prohibited application of automated hydrologic analysis algorithms in such a catchment.

The Upper Washita Catchment EDNA project demonstrates how CatchmentSIM was able to generate superior catchment boundaries and calculated stream networks than the approaches adopted by the USGS. These improved results are largely due to CatchmentSIM's improved flow routing algorithm and the PFS flat and pit cell resolution algorithm.

Chapter 7 will draw conclusions and outline important research questions that could provide a foundation for future research in this field.

7 CONCLUSIONS AND FUTURE WORK

7.1 INTRODUCTION

This research project has aimed to improve on existing techniques for automated hydrologic analysis of GIS data sets and coupling of these approaches with lumped hydrologic models. It has involved the development of CatchmentSIM, a new GIS software product designed to overcome limitations in existing approaches to the problem.

A comprehensive literature review was undertaken to assess the current state of research in the field. It was found that there was significant potential for improvement on current approaches. New algorithms and an associated GIS software framework were formulated as documented in Chapter 3. Following development of the algorithms and the CatchmentSIM application, the algorithmic methodologies and subsequent capabilities were described in Chapter 4. Chapter 5 documents a comparison between the CatchmentSIM algorithms and current techniques, as well as demonstrating how CatchmentSIM's hydrologic and geomorphologic analysis tools could be applied to formulate a better understanding of the hydrologic properties of subcatchments within a lumped hydrologic model. Chapter 6 reported on two case studies that were completed using the CatchmentSIM software including comparisons to existing approaches.

Conclusions from the project and suggestions for future work are outlined in the following sections.

7.2 RELEVANT CONCLUSIONS

Development of the CatchmentSIM software and its internal algorithms has contributed to research in a number of fields. These include DEM interpolation from contour and watercourse alignment data, hydrologic conditioning of raster DEMs, flow routing over raster DEMs, representation of urban environments in automated DEM analysis and hydrologic / geomorphologic analysis of subcatchments in lumped hydrologic models. While detailed research into any one of these fields could form the basis for several large research projects, this project has aimed to examine all of these fields in the context of their overall contribution to functionality and usability of a real software application. Ultimately, whilst improvements have been made to many facets of algorithm accuracy, it has not come at the cost of speed or simplicity. In fact, CatchmentSIM is simpler to user than most available software products due to its highly visual graphics orientated interface.

The DEM interpolation algorithm that was designed for and incorporated within CatchmentSIM includes a number of improvements to traditional profile based interpolation algorithms. These include vector search paths instead of raster search paths, variable algorithm search ray frequency and flat cross-section discounting. These result in an improved interpolation surface that generates catchment and subcatchment boundaries that closely match those derived manually from the contours and watercourse alignments. CatchmentSIM also allows for importing of DEMs that are remotely sampled or interpolated by alternative techniques in other software applications. The watercourse integration algorithm greatly improves the interpolation surface and effectively preserves the observed flow network in the resulting DEM surface.

The PFS algorithm incorporated within CatchmentSIM includes a number of improvements over previous implementations of this approach. These improvements include elevation prioritised processing order and a number of additional parameters designed to optimise algorithm implementation as described in Section 4.5.2 (*page 137*). CatchmentSIM's implementation of the PFS algorithm has been shown to create more realistic fractal stream networks in large flat areas, which are common in DEMs of limited vertical precision. This is particularly relevant because most DEMs currently being produced still have limited vertical precision. For example the SRTM DEMs currently being compiled have a vertical precision of 16 metres. As a result, these DEMs will have large flat areas in many topographic regions.

The flow routing algorithm incorporated in the CatchmentSIM software includes a number of important modification over Lea's (1992) original algorithm design as documented in Section 4.6 (*page 143*). These improvements successfully overcome the previous problems with this algorithm resulting from approximating a rigid plane through four points, which could cause flow paths to flow towards, and cross into, grid cells of higher elevation. CatchmentSIM's flow routing algorithm has been shown to produce more realistic hill slope flow paths than alternative techniques as demonstrated in Section 5.2 (*page 172*). Furthermore, CatchmentSIM's flow routing algorithm has been shown to calculate more realistic stream networks than the D8 method utilised by all other available software products in the field (*as outlined in Section 3.6, page 110, even applications using multiple direction flow algorithms switch to the D8 method in stream channels*). The improvements to the stream network resulting from the flow routing algorithm provide follow-on benefits to all automated catchment break-up, hydrologic analysis, and associated statistics that utilise the stream network in their calculations.

As a further consequence of CatchmentSIM's improved flow routing algorithm, several new forms of hydrologic and geomorphologic analysis are possible. These include overland flow path length frequency distributions and drainage density versus SAT curves. As demonstrated in Section 5.4 (*page 181*), these analysis tools can provide valuable insight into the hydrologic properties of subcatchments and can facilitate a more objective foundation for assignment of lag parameters in lumped hydrologic models than traditional approaches. Other hydrologic analysis capabilities of CatchmentSIM include assessment of the geomorphological correctness of stream networks, Horton / Strahler analysis and hypsometric charting. These tools are all improved from previous implementations due the advances in flow routing incorporated within CatchmentSIM.

The hydraulic control tools implemented within CatchmentSIM are unique to this software product and no similar capabilities were found in any of the software reviewed in Section 2.11 (*page 84*). These tools allow automated hydrologic analysis of DEMs to be applied in urban areas where DEMs are not entirely indicative of local topography. These tools were shown to accurately represent the effect of urban features on stormwater flow in the case of the Holland Park Local Stormwater Management Plan (LSMP) as documented in Section 6.2 (*page 198*).

The CSTalk macro language developed during this project allows for coupling between CatchmentSIM and any other hydrologic model. The language is simple, text file based, and does not require extensive programming experience. It may also be used to create customised report formats to improve quality control and minimise data entry errors. Presently, the potential for GIS aided parameterisation of hydrologic models has gone largely unrecognised within Australia due to the compatibility and coupling problems that exist between overseas designed GIS software, and the local Australian lumped hydrologic models that have been adopted by the scientific community. The CSTalk macro language has overcome this barrier and currently facilitates seamless coupling with a full range of Australian lumped hydrologic models including RAFTS-XP, WBNM, URBS, RORB and DRAINS, as well as the popular US model HEC-HMS.

Two case studies were presented in Chapter 6 which profiled some of the research that has been completed around the world using CatchmentSIM. The Holland Park Local Stormwater Management Plan project demonstrated CatchmentSIM's urban modelling capabilities as well as the advantages offered by CatchmentSIM's advanced flow routing and flat and pit cell resolution algorithms. The Upper Washita Catchment EDNA project compared subcatchment boundaries and stream networks generated by CatchmentSIM and those developed by the EDNA methodology. The advantages of the CatchmentSIM flow routing algorithm and PFS algorithm were clearly established by this comparative exercise.

In its entirety, CatchmentSIM has proved to be an effective and simple tool for more accurate parameterisation of lumped hydrologic models. It has successfully met the objectives outlined in Chapter 3 as evidenced by the analysis documented in Chapters 4, 5 and 6, and by its adoption by the wide profile of users illustrated in **Figure 6-2** (*page 196*) and listed in **Appendix D**. These accomplishments aside, there is still a wide body of research that could be completed to further investigate and extend the algorithms embodied within the CatchmentSIM application as outlined in the following section.

7.3 RECOMMENDED FUTURE WORK

CatchmentSIM is an on-going software development project. In November of 2003, the Cooperative Research Centre for Catchment Hydrology (CRC-CH) invited CatchmentSIM to form a component of its Catchment Modelling Toolkit (http://www.toolkit.net.au). The Toolkit is designed to accumulate leading Australian hydrologic modelling products and help facilitate their on-going development. As such, work on the software will continue and user feedback is regularly prompting the introduction of new features. Some of the key software improvements that are planned to be incorporated into CatchmentSIM in the near future are:

- Program algorithms should be modified to be more memory efficient for processing of massive grids in a similar manner to the r.terraflow and RiverTools algorithms (*see page 90*). These changes will not have any effect on the results of the algorithms, merely on the speed and grid size capabilities of the software.
- Provide support for the latest GIS data-models including ESRI personal geo-databases.

However, aside from general software development there are number of other investigations that would further improve and add to the knowledge derived from this project. These investigations include:

- Calibration exercises undertaken in various lumped rainfall runoff models to verify and describe any relationship between lag coefficients and CatchmentSIM derived network topology parameters such as the bifurcation ratio.
- The spatial data model and graphics engine used by CatchmentSIM has good potential to be used as a post-processor for hydrologic and hydraulic model results. For example, CatchmentSIM could easily be modified to develop flood inundation mapping from hydraulic flood modelling results. This would further encourage CatchmentSIM’s role as a geographic framework from which hydrologic and hydraulic models can be tightly integrated.

- Non-linear hydrologic routing formula based on slope and upstream contributing area for each cell could be incorporated into the software, in order to calculate standard response hydrographs for each subcatchment. These could be used to compare the hydrologic characteristics of project subcatchments and serve as a basis for assignment of lag parameters in subsequent lumped hydrologic models.
- CatchmentSIM could be coupled with prominent lumped hydrologic models to investigate the effect on flow hydrographs of incremental discretisation of subcatchment networks based on stream networks generated at lower and lower SAT values. This would aim to determine if a relationship exists between the shape of the runoff hydrograph and the quantity of subcatchments. Such a relationship would be undesirable and would indicate scale bias in the flow routing equations. This issue is important to address if such routing methodologies are to be applied in distributed hydrologic modelling (*treating individual grid cells as model subcatchments*) since if such an approach is to improve on lumped subcatchment modelling, it would need to be relatively independent of the scale of the underlying raster grid.
- After the aforementioned investigations are completed, the potential exists for integration of distributed hydrologic and hydraulic modelling algorithms to allow modelling from within CatchmentSIM on an individual grid cell basis.

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APPENDIX A

CATCHMENTSIM TUTORIAL

CATCHMENTSIM TUTORIAL

OVERVIEW

This tutorial will take you through the basic steps involved with using CatchmentSIM, from importing GIS source data to catchment partitioning, hydrologic analysis and integration with a back-end hydrologic modelling package. In case this is your first use of CatchmentSIM, installation instructions have also been provided.

This tutorial requires six data files, which hold the GIS source information in Mid/Mif format (*MapInfo data exchange format*). These files are:

- **contour-data.mid** & **contour-data.mif**
- **stream-data.mid** & **stream-data.mif**
- **impervious-areas.mid** & **impervious-areas.mif**

A topographic image file has also been included called **tut-topo.jpg**

If these files are not included with this tutorial package, you may download them from the CatchmentSIM website (http://www.uow.edu.au/~cjr03).

This tutorial is written in a concise format from an instructional perspective. Comprehensive information regarding all of the internal program algorithms can be found on the website.

INSTALL PROGRAM

If CatchmentSIM is not installed on your computer then you must do this prior to using the application.

CatchmentSIM is installed using InstallShield®, consequently, installation and un-installation are very simple and safe. The program can be installed by simply double clicking the *CatchmentSIM.exe* executable and following the prompts. The program can also be easily removed by using the Remove Programs command in the Control Panel and selecting CatchmentSIM from the scroll-box.

On first use of CatchmentSIM you will be prompted to register the software. Registration is free and will only take a couple minutes via the CatchmentSIM website. You will need to sign up as a site member and then register by entering your site-access username and password as well as the registration code that is displayed on the CatchmentSIM registration form. The site will then generate a unique access code for you to type into the registration screen. Following acceptance of the access code you are free to use the program (*you will not be prompted for registration again until you update to a newer version*).

SETUP PROJECT

To begin a new project, select **New Project** from the **File** menu.

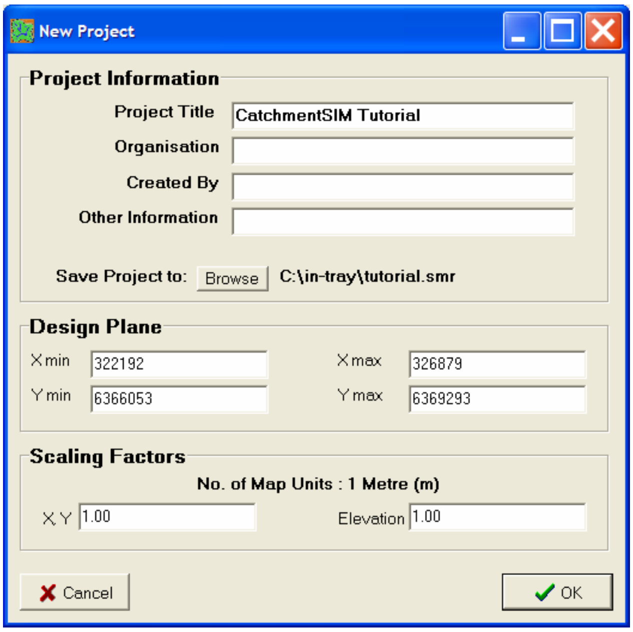
Enter any relevant information in the *Project Information* text fields (*these can be left blank if you wish*).

Click the *Browse* button and enter the filename and location of your project.

Enter the X & Y design plane extents for the project. The region defined by these coordinates is the design plane and all source data will be clipped at its intersection with this rectangle. This ensures that file sizes and processing times are minimised. For this tutorial select the following design plane extents:

- Xmin: 322192
- Ymin: 6366053
- Xmax: 326879
- Ymax: 6369293

The scaling factors enable coordinate systems and elevations scales that are not in metric m x m grid formats to be used with CatchmentSIM. In this case, the grid and elevations are in metres and hence the scaling factors should be assigned the default value of 1.00.



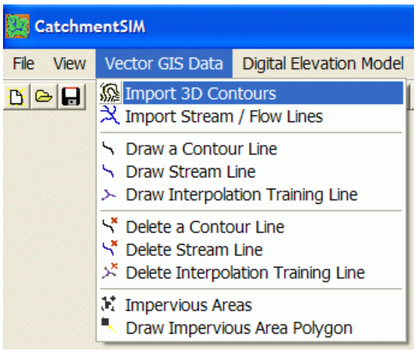
Click OK.

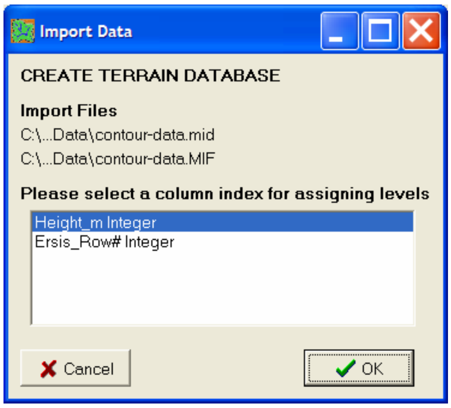
IMPORT SOURCE DATA

To import vector contour source data, use the **Import 3D Contours** menu item from the **Vector GIS Data** menu.

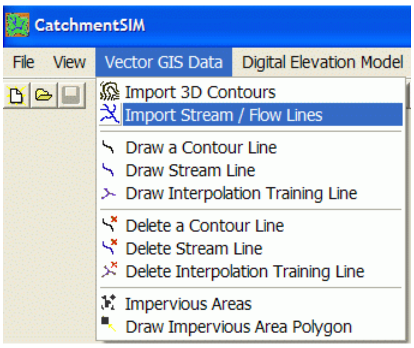
Select the mid/mif files for import, in this case *contour-data.mif*. 3D vector data files in Mid/Mif format consist of two files, one with the 2D vector line network coordinates (*the *.mif file*) and the other consisting of a comma separated value (CSV) file that lists the various attributes of each line or polyline (*the *.mid file*). Hence, the elevation of each line is stored as a 'column' in this file. You need to select the column that stores the elevation data from the list of column titles, which are displayed in the *Import Data* form.

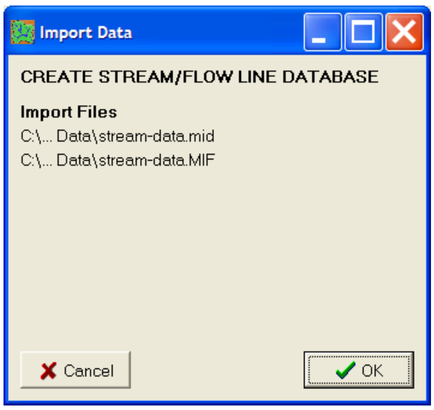
For this tutorial, elevation data is stored in the column titled *'Height m Integer'*. Select this column in the scroll-box and press *OK*. The 3D contour data should now have been imported into the project.



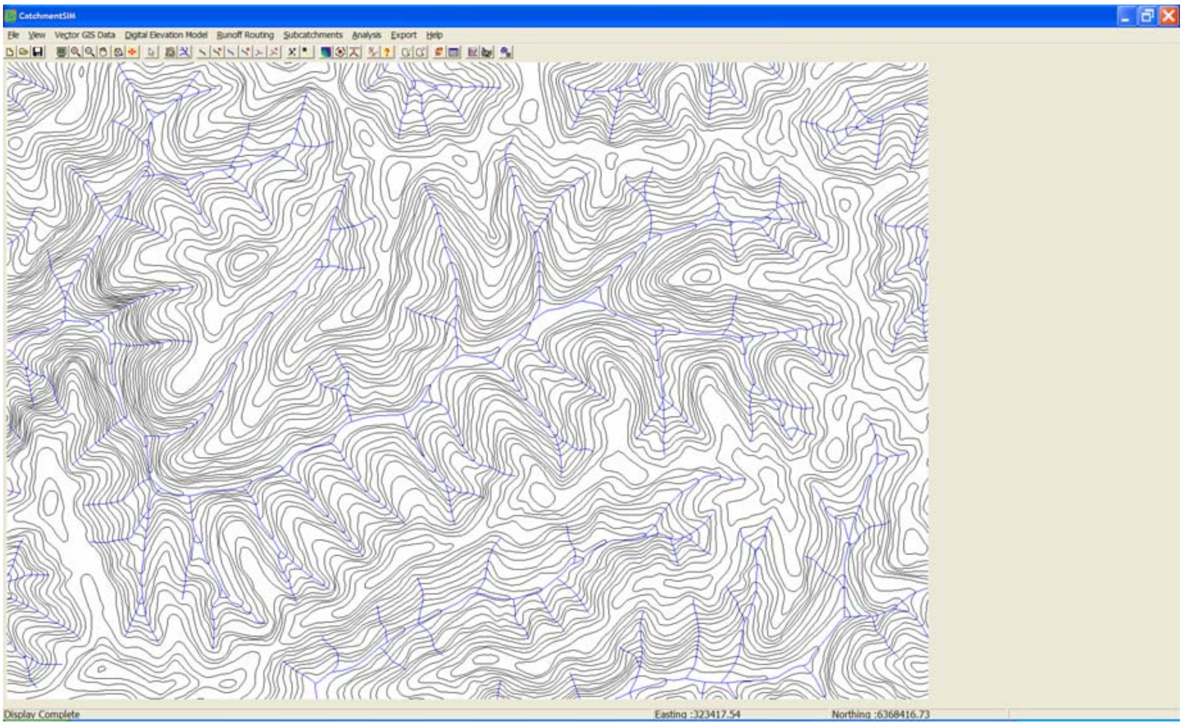


If available, stream data is very useful in a CatchmentSIM project. To import this data follow a similar procedure using the **Import Stream / Flow Lines** command from the **Vector GIS Data** menu. This time, you do not need to select a column number for elevation assignment since stream data is 2D only, so just press *OK*.





At this stage you should be able to see the imported contour and stream data on the screen. Should you wish to turn one or more of these layers off or change their colours, try using the *View Attributes* form by selecting **View Attributes** from the **View** menu.



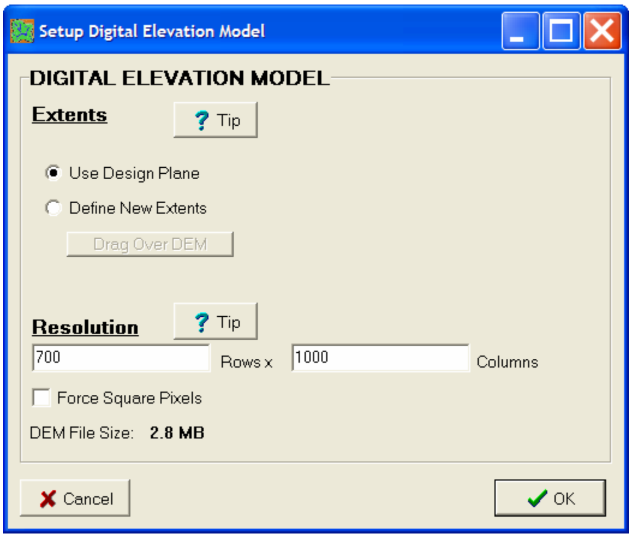
If you wish, you can manually digitise additional contours or streams directly on the screen into a CatchmentSIM project. This shouldn't be necessary for this tutorial.

DEVELOPING THE DIGITAL ELEVATION MODEL

The Digital Elevation Model (DEM) forms the foundation of the bulk of CatchmentSIM tools. The DEM is a grid structure (*raster*) where every grid cell is given an individual elevation value. To setup the DEM select **Setup Digital Elevation Model** from the **Digital Elevation Model** menu. This form prompts you to enter coordinate extents for the DEM or use the same extents as the project. This allows you the opportunity to select a smaller area than your project design plane for analysis. Generally, the region bounded by the DEM extents should be the smallest rectangle possible that fully encloses the catchment of interest.

For this tutorial, using the existing design plane will be fine, so just select the *Use Design Plane* radio-button.

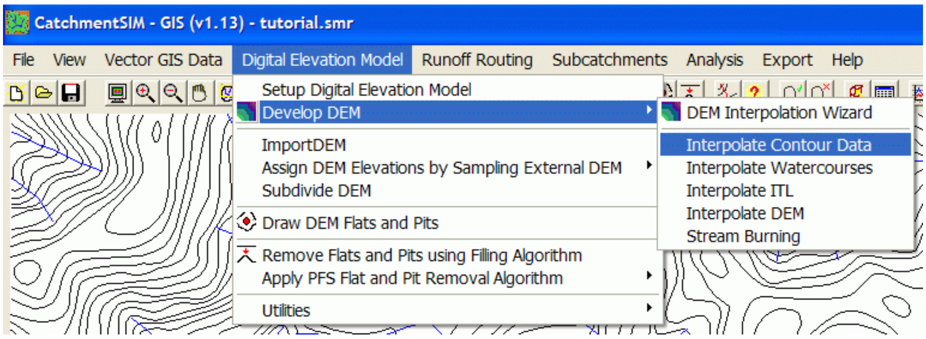
The file size and processing times for CatchmentSIM projects are largely effected by the size of the DEM, where size refers to the total number of grid cells (*cells*) rather than the spatial extents of the DEM. For this tutorial, set the number of rows and columns of the DEM to **700 rows** and **1000 columns** (*700,000 cells*) and press OK. If you are using a slow computer or have less than 32 MB of RAM then you may wish to choose a coarser resolution.



At this stage, the DEM has been created, yet cell elevations have not been defined. The process of determining an elevation for every cell is achieved by a number of steps, namely:

- Rasterisation of contour data;
- Interpolation of streams / flow lines (*if available*);
- Interpolation of Interpolation Training Lines (ITLs) (*if available & required*);
- Interpolation of the DEM; and,
- Stream burning.

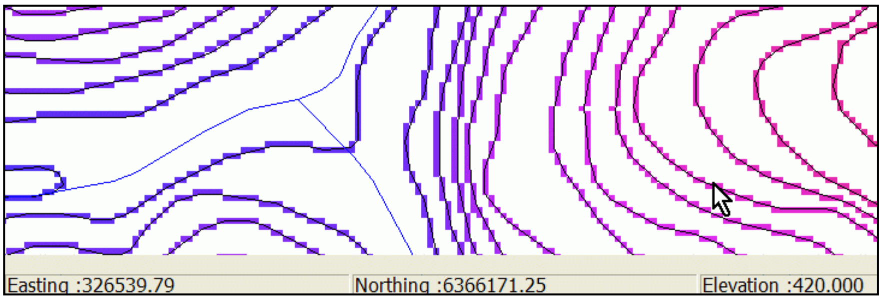
These steps have been automated in a *DEM Interpolation Wizard* but can be accessed individually from the **Develop DEM** submenu located in the **Digital Elevation Model** menu. For the purposes of this tutorial we will use these commands individually so you are able to see their effect on the DEM.



Rasterisation of Contour Data

Contour data is transferred into the DEM by assigning selected cells that underlie the vector contour data with the elevation attribute of the contour line.

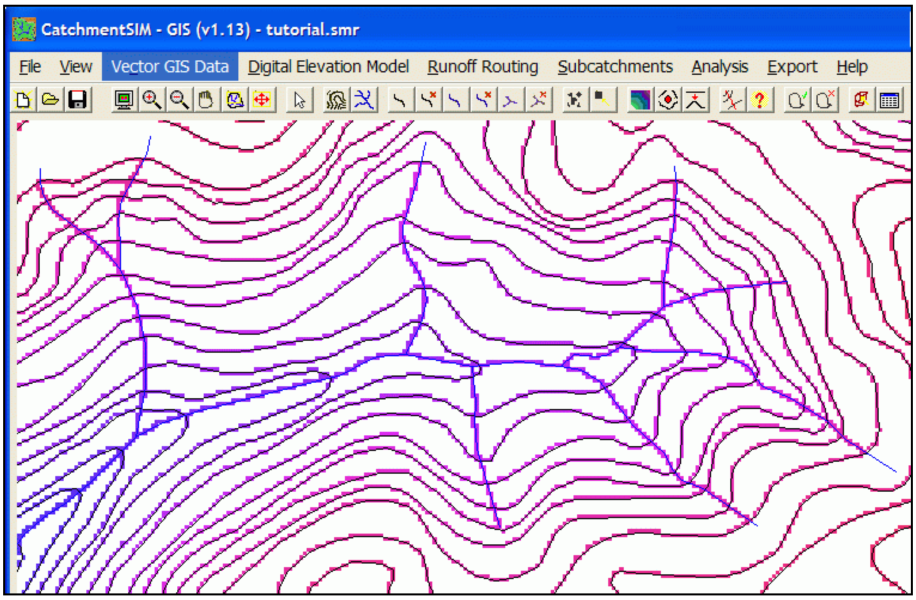
Select **Interpolate Contour Data** from the aforementioned submenu. After this process is complete you should be able to see the elevation colour-coded assigned DEM cells underlying the vector contour data. You should also be able to see the elevation of a DEM cell in the lower right hand corner of the screen when you position the mouse over an assigned DEM cell.



Interpolation of Streams / Flow Lines

Since the imported stream GIS data is 2D only, it can not be incorporated into the DEM in the same fashion as the contour data. Rather, the streams are incorporated by interpolating values of cells along the stream alignments in between intersected contour lines.

Select **Interpolate Watercourses** from the aforementioned submenu. You should see that cells underlying stream alignments have been assigned an interpolated elevation value between the intersected contour lines. This provides a valuable representation of troughs in the terrain and results in a much more realistic interpolated DEM.



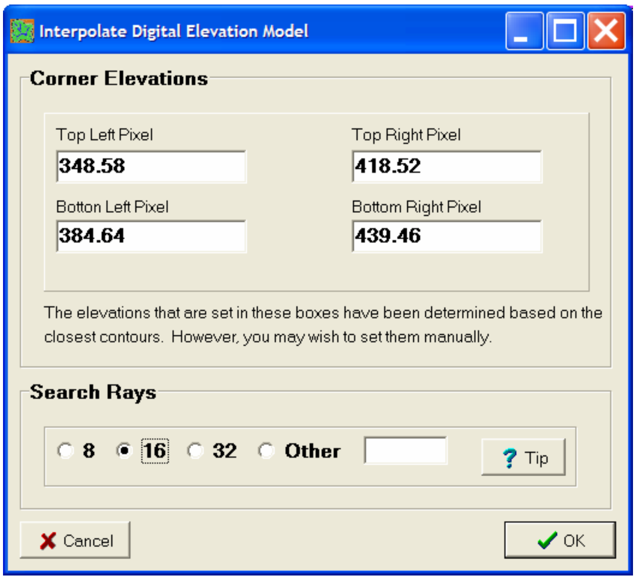
Interpolation of Interpolation Training Lines (ITL)

ITLs are lines that can be digitised directly on the screen into the CatchmentSIM project. These lines can be added to a project to improve the DEM interpolation and are generally placed along expected ridge lines or flow-paths. ITLs should not be necessary for this tutorial.

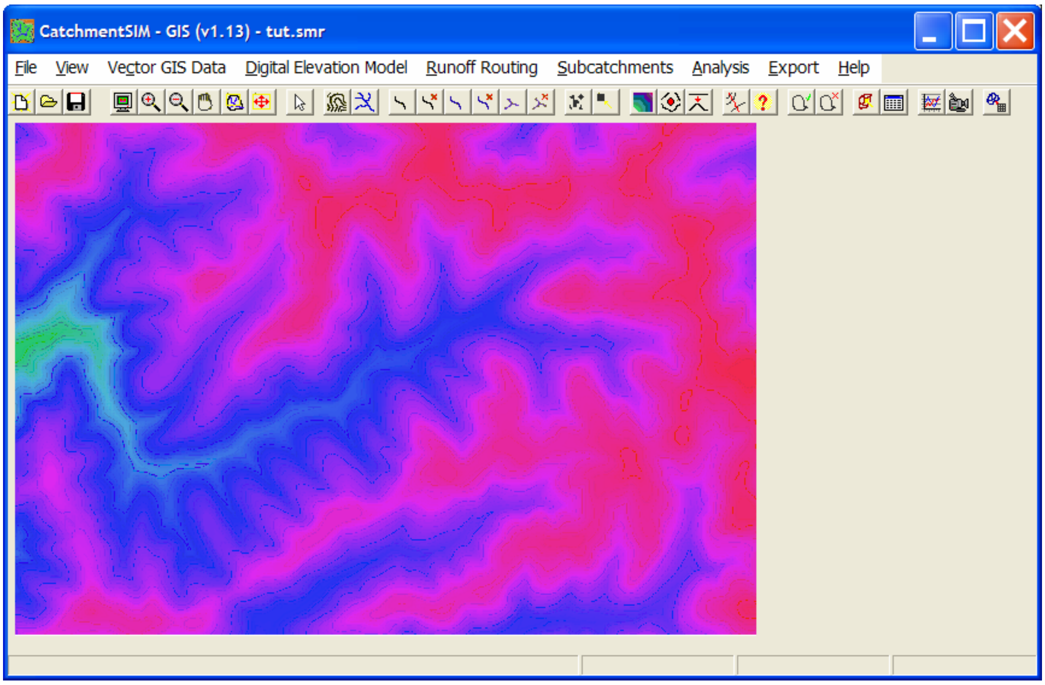
Interpolation of the DEM

At this stage, you will notice that cells underlying contour or watercourse lines have been assigned an elevation (*and a corresponding colour*), however the bulk of the DEM cells will still be unassigned. These cells are assigned elevations by interpolating their value from surrounding cells.

Select **Interpolate DEM** from the aforementioned submenu. You need to assign corner elevations for the DEM. The algorithm has 'guessed' these values by looking at nearby contours but you can adjust them if necessary. For this tutorial, the current values will suffice. The number of interpolation rays indicates the number of directions the interpolation algorithm will look in when searching for nearby assigned cells. The higher value you select, the more accurate the DEM will be and the longer the interpolation will take. *16* rays should be sufficient for this tutorial. Press *OK.*



Following interpolation of the DEM, you should see that all DEM cells have been assigned elevation values.



Stream Burning

At this stage, you may wish to implement stream burning. This is the process of lowering all cells that underlie a stream line by a set increment (*default of 0.5 m*). This has the effect of ensuring that once a cell flow path intersects a stream line, flow will be forced to follow the stream until leaving the catchment. Otherwise, flow paths may deviate slightly from the imported stream network in order to follow the steepest downslope path (*this is not always represented by the imported stream network*). Stream Burning is not required, but it is recommended if the automated catchment breakup algorithm is to be used.

For this tutorial stream burning should be applied. Select **Stream Burning** from the **Develop DEM** submenu of the **Digital Elevation Model** menu.

HYDROLOGIC CONDITIONING OF DEM

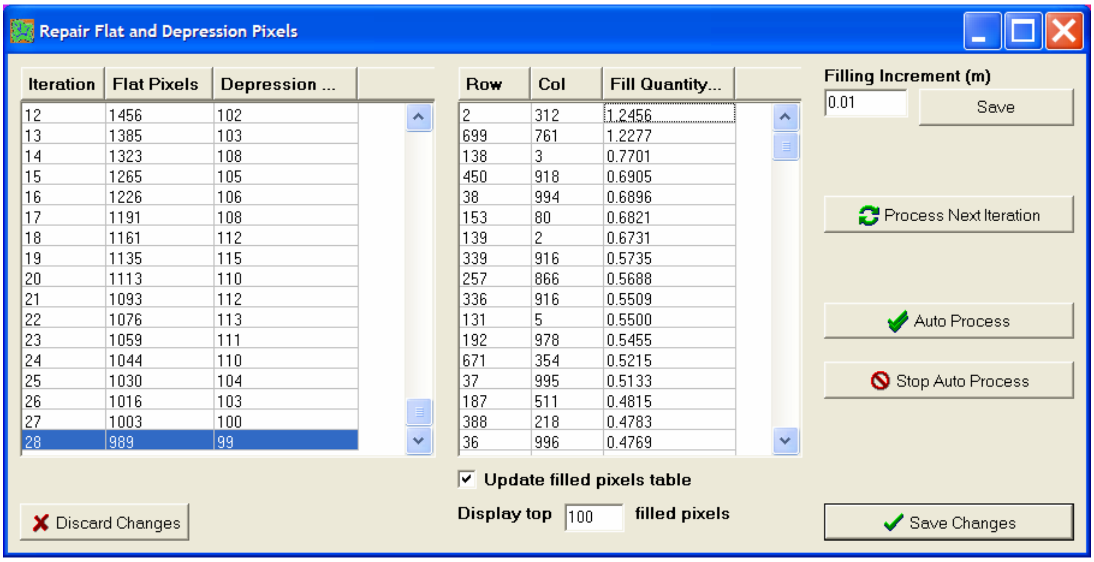
Although the DEM has now been developed, it may not yet be ready for use to delineate the catchment. The DEM will probably contain flat or pit cells, that is, cells that are either equal or lower in elevation than the lowest of their neighbouring cells. These cells are usually the result of lack of source data definition or anomalies resulting from the interpolation algorithm.

Flat and pit cells can be displayed by selecting **Draw DEM Flats and Pits** from the **Digital Elevation Model** menu. You should see that many flat and pit cells have been created, most at the top of hill crests where the interpolation algorithm has found the same elevation value in all directions due to the final 'ring' contour and has consequently flattened off the hill crest. There is an algorithm to fix this problem and ensure smooth drainage paths over all sides of each hill.

Two algorithms have been introduced into CatchmentSIM to help remove flat and pit cells from a Digital Elevation Model. Firstly, an iterative filling algorithm has been incorporated to treat the aforementioned hill-crest anomalies, and other simple cases where flat and pit cells have been created by interpolation in areas of low relief or low contour definition. Secondly, a more advanced Priority First Search (PFS) weighted graph breaching algorithm has been introduced to find outlets for any remaining flat or pit cells. The PFS algorithm can resolve any flat or pit cell provided there is a cell with a lower elevation somewhere in the DEM. The algorithm finds the best solution based on a priority function and determines a flow-path from each flat or pit cell to a nearby outlet, and lowers all cells along this path to form a linear downslope flow-path. The downslope flow-path is optimised by the priority function to traverse the lowest possible pass and have the shortest possible flow length.

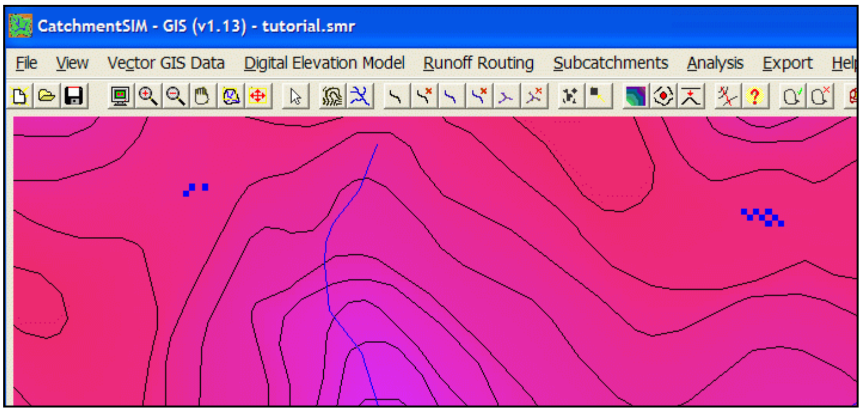
In the case of a CatchmentSIM interpolated DEM (*as distinct from an imported DEM*) it is important to first treat hill-crest flat areas with the iterative filling technique before using the PFS algorithm. This algorithm firstly, raises pit cells to the elevation of their lowest neighbour, which converts them into a flat cell and secondly, all flat cells are raised by a set increment. This is an iterative procedure that will gradually remove flat and pit cells and raise hill crests in a smooth manner ensuring that the centre of the hill crest will have the highest elevation.

To do this select **Remove Flats and Pits using Filling Algorithm** from the **Digital Elevation Model** menu. The form will display the current number of flat and pit cells. The filling increment can be edited in the Top Right corner of the form. You can undertake one iteration of the filling algorithm by selecting *Process Next Iteration*, do this now. You should see that a significant proportion of the flat and pit cells have been removed and the list on the right will display the largest filling increments that were applied. Don't be alarmed if some of these numbers are large as they represent the occasional deep pit cell anomaly. To speed up the process select *Auto Process* and keep watch of the number of pits and flats and largest fill increments as they progress. Once the flat cell count is down to a satisfactory level (*1000 for this tutorial*) stop the *Auto Process*. Remember, most flat or pit cells are outside of your catchment on the sides on the DEM where they will not effect the project. Furthermore, you can always come back and repair more flat and pit cells with the *Repair Flat or Pit Cells* form.

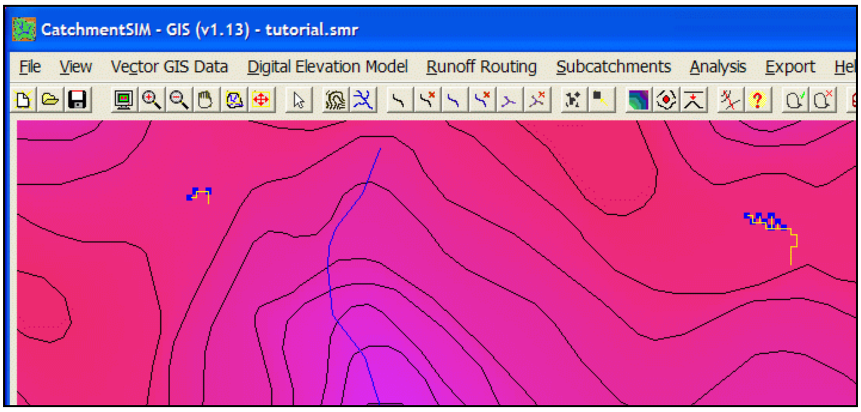


For this tutorial, anything less than 1000 flat cells should be satisfactory. Press *Save Changes*.

If you now re-draw the screen (F1) and re-draw the flat and pit cells you will notice that the flat areas at the hill-crest have been removed. However, some flat and pit cells within the expected catchment have not been removed. This is due to their position in areas of limited contour information.



These flat and pit cells could have been avoided by inserting Interpolation Training Lines in these areas prior to interpolation. However, they can also easily be treated by applying the PFS algorithm. They can be treated by clicking on these cells individually using the **Individual Pixel** option in the sub-menu of the **Apply PFS Flat and Pit Removal Algorithm** option in the **Digital Elevation Model** menu or treated as a whole by selecting the **Entire DEM** option in the same sub-menu. To save time, select the **Entire DEM** option.

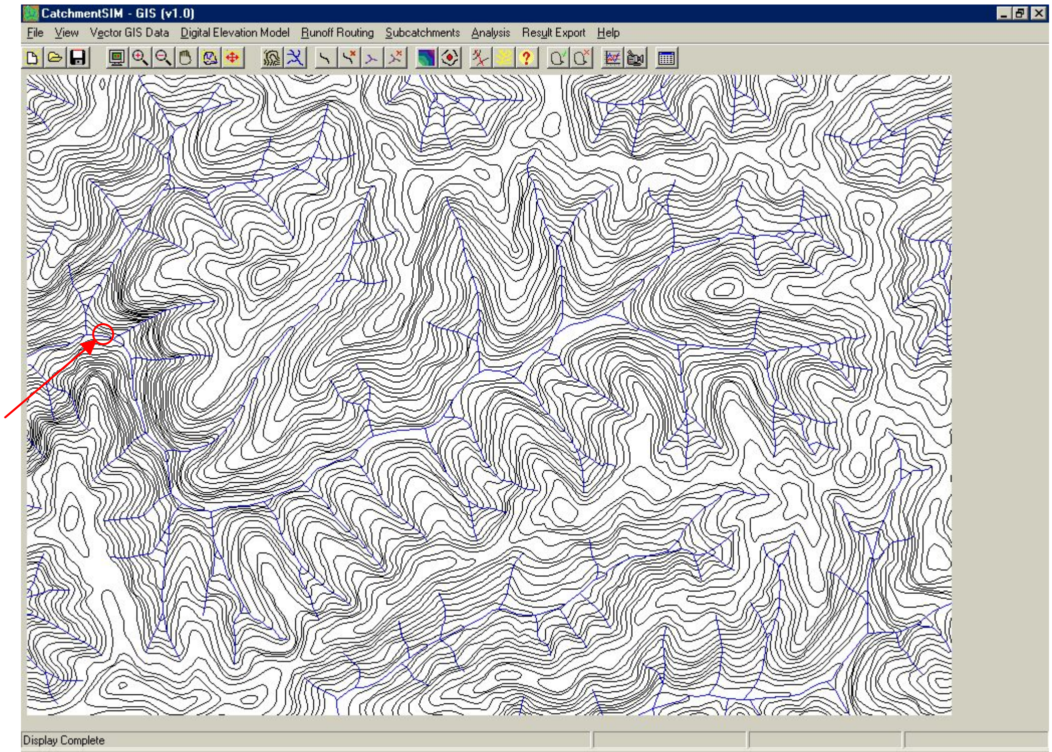


After completion of this algorithm you should notice that the flat and pit cells have been mapped to an optimised downslope outlet cell and this is indicated on screen by a yellow line. Cell elevations along this line have been linearly lowered to provide a downslope flow-path for the original flat or pit cell. If you re-draw the screen (F1) and re-draw flat and pit cells you should now notice that none exist within the expected catchment boundary.

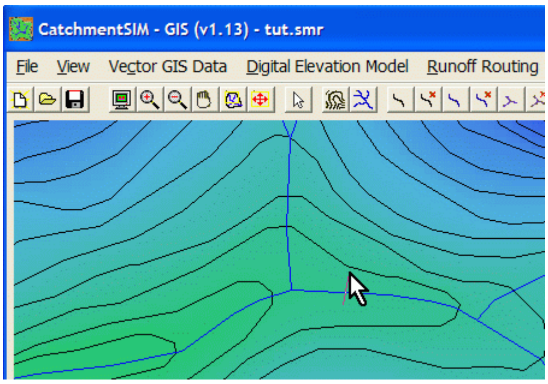
CATCHMENT DELINEATION

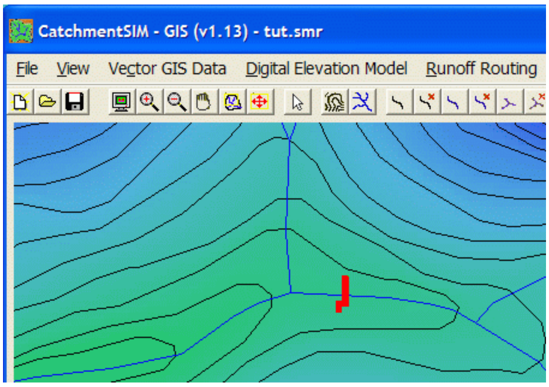
At this stage your DEM should be ready for use in delineating the catchment. To test flow routing on the DEM try mapping flow from a selection of cells within the catchment. Do this by selecting **Draw Pixel Flow Path** from the **Runoff Routing** menu and clicking on some points on the screen that you expect to be within your catchment. You should see the downslope flow path of these cells is mapped until they reach a DEM boundary or a flat or pit cell. Provided they continue past the point where you plan to put your catchment outlet, catchment delineation should work.

Identify your catchment outlet by drawing a short line where you wish to place your catchment outlet, do this by selecting **Add Subcatchment** from the **Subcatchments** menu and clicking on the screen. Click once to start the line, then click on additional vertexes. Finally, right click to end the line and save the outlet cells. For this tutorial, place the catchment outlet line in the position shown below.



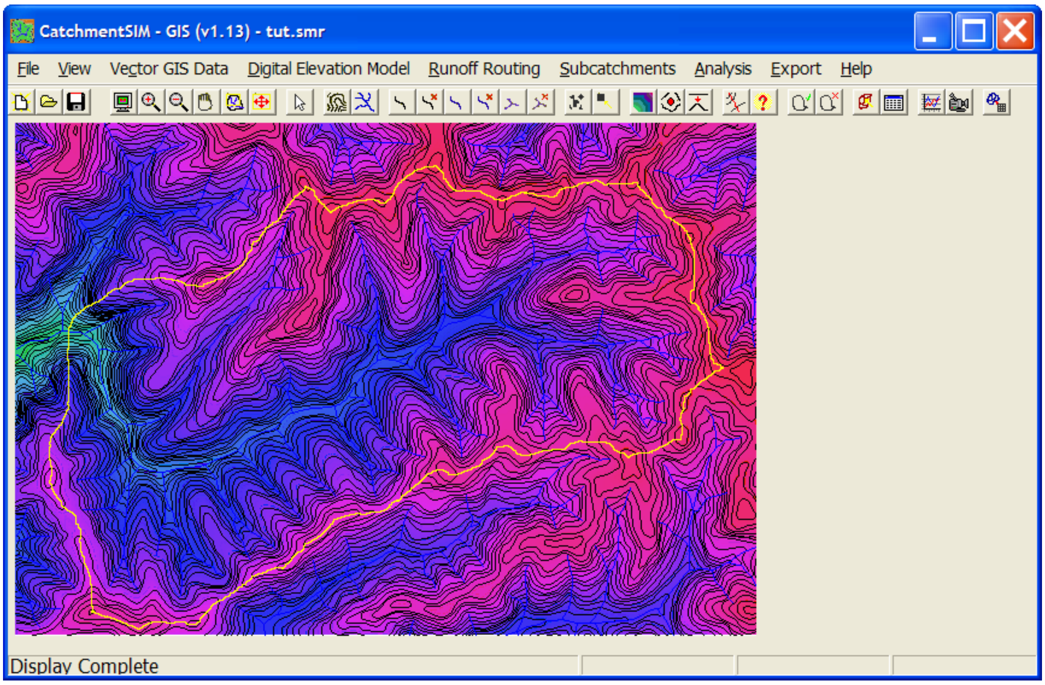
Despite drawing a line to identify your catchment outlet, the outlet is actually recorded as a group of cells. Display of the outlet cells can be toggled in the *View Attributes* form.





You can now identify subcatchment outlet points if you wish but in this case we will first delineate the entire catchment, do this by selecting **DEM Wide Flow Processing** from the **Runoff Routing** menu. This is the most time-consuming algorithm in the program and is effectively drawing flow path maps similar to few you did previously, for every cell in the DEM and recording which ones flow through the cells you have designated as your catchment outlet.

Following completion of the flow processing, the catchment boundary should appear (*try changing the colour or turning off the DEM background if you are having trouble seeing it*). Problems with any flat or pit cells within the catchment will become obvious at this stage and should appear as holes in the catchment. Furthermore, any areas that could benefit from the placement of ITLs will become apparent.



CATCHMENT PARTITIONING

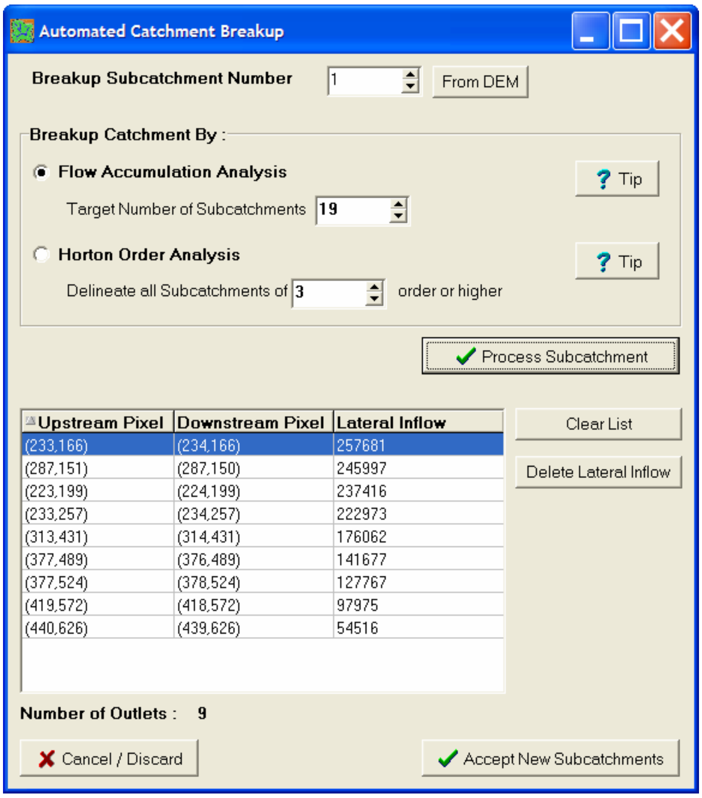
Subcatchment Delineation

Catchment partitioning is the process of breaking up a catchment into a network of subcatchments with joining links. Subcatchments are identified by their outlet cells similarly to the catchment outlet. This can be done manually (*as for the catchment*) or by taking advantage of CatchmentSIM's automatic catchment partitioning algorithms.

For this tutorial, we will be using one of the automatic catchment partitioning algorithms, select **Breakup Catchment** from the **Subcatchments** menu. The subcatchment you wish to partition is number 1 (*since you only have one subcatchment delineated*) but you can also identify the subcatchment to partition by pressing *From DEM* and selecting the subcatchment by clicking on it (*the subcatchment should be highlighted when the mouse is positioned over it*).

The catchment is currently delineated into 1 region but we want to partition it into several subcatchments. This can be achieved using one of two available techniques. Either subcatchment outlets can be identified at the largest jumps in flow accumulation values (*designed to break the catchment into similar size subcatchments*) or subcatchment outlets can be identified at junctions in the predicted stream network of particular Strahler / Horton stream orders (*see Vector Stream Network below*). For this example, use the first option.

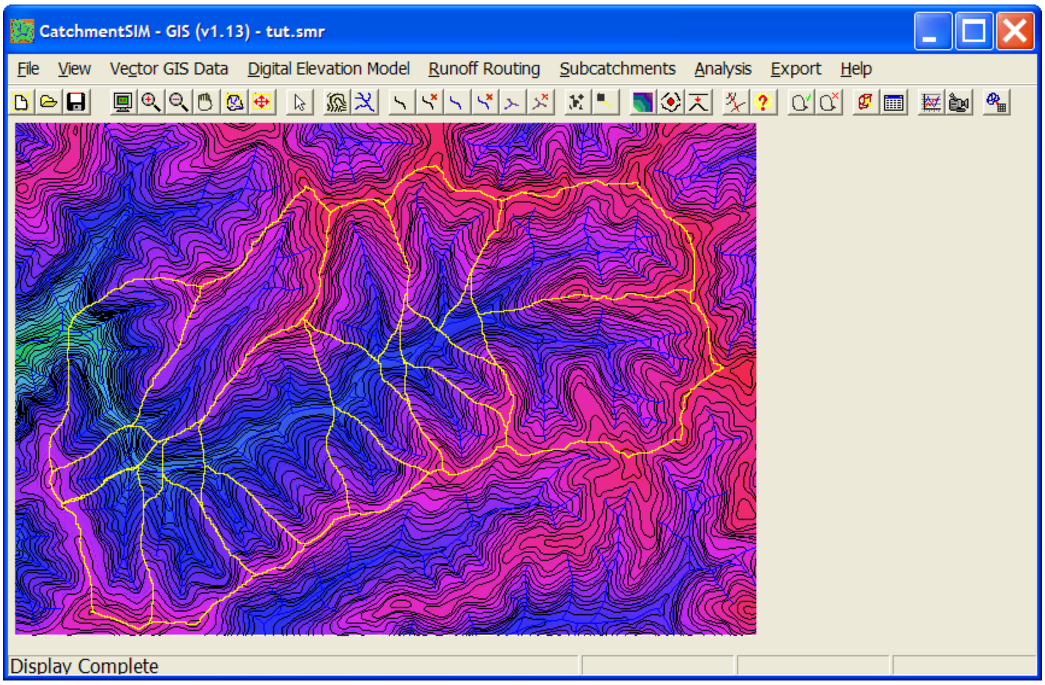
The flow accumulation jump analysis method works by identifying major lateral inflow junctions within the drainage network of the catchment and assigning two sets of outlet cells, one above and one below the lateral inflow. The target number of subcatchments will always be an odd number as the catchment is already one region and two more will be defined for every lateral inflow junction that is identified. For this tutorial, set the target number of subcatchments to 19. At this point click *Process Subcatchment*.



The list towards the bottom of the form should now be filled with several lines of data, nine in this case. These are the lateral inflow junctions that have been identified to serve as the locations for subcatchment outlets. You should take a quick look at these numbers to ensure that they the same junction hasn't been picked up twice and the lateral inflow quantities are significant enough to warrant subcatchment delineation. If you wish, you can remove a lateral inflow junction using the Delete Lateral Inflow button (*this will reduce the resulting number of subcatchments by two*). For this tutorial, this should not be necessary. Click Accept New Subcatchments.

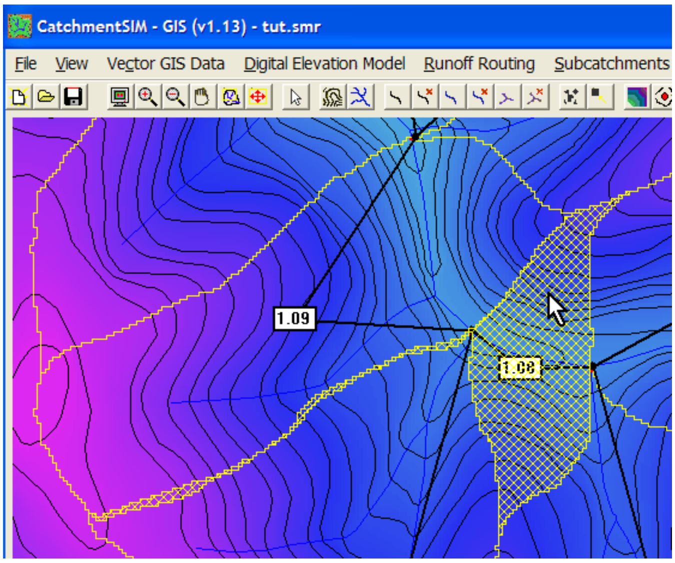
CatchmentSIM will prompt you to decide if you wish to refine this subcatchment now or wait until later. If you select yes then the program will initiate Flow Processing for only those cells within the subcatchment. However, in some cases you may wish to select no, identify further subcatchments by hand or automatically partition other subcatchments and then redo DEM Wide Flow Processing at a later time. For this tutorial, select yes.

After this process is complete, you should see that the catchment has been partitioned into the designated number of subcatchments. At this stage, you can add additional subcatchments, delete existing subcatchments or automatically partition other subcatchments.

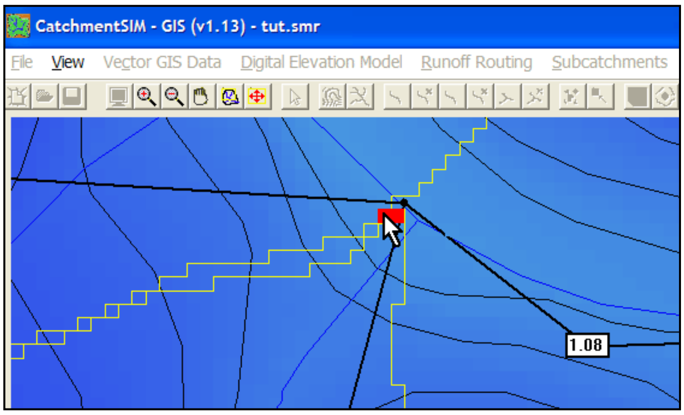


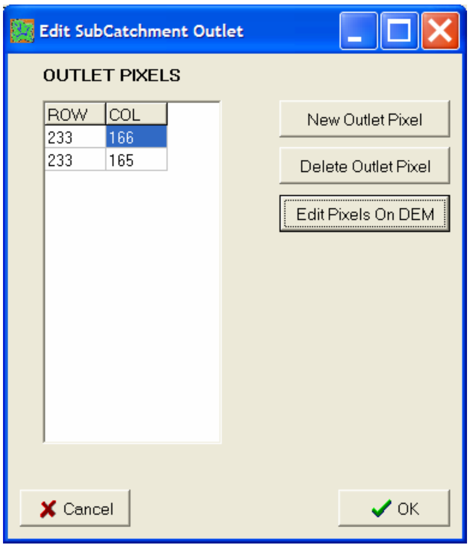
You may also need to fix up any small drainage anomalies that have arisen at subcatchment outlets where a small parcel of terrain is seemingly assigned to the wrong subcatchment. These anomalies are due to the assignment of subcatchment outlets by using only one outlet cell and can be easily fixed by assigning additional outlet cells to the subcatchment to better define its outlet (*use* **Edit Subcatchment Outlet Cells** *from the* **Subcatchments** *menu*).

For example, this may have occurred in this tutorial along the boundary between subcatchments 1.09 and 9.01 (*to turn on subcatchment labels, open the* ***View Attributes Form****, ensure Nodal Link Arrangement is selected and press OK*). Zoom into this region using the *Zoom Window* function in the *View* menu and clicking a rectangle around this area. Select the **Edit Subcatchment Outlet Cells** option from the **Subcatchments** menu. This option will cross-hatch subcatchment areas when the cursor is positioned over them. By positioning the cursor over subcatchment 1.08 you may notice that cells that you would expect to be in subcatchment 9.01 appear to be included in subcatchment 1.08. This has occurred because the flow path from these cells has 'just missed' the 9.01 outlet cell.

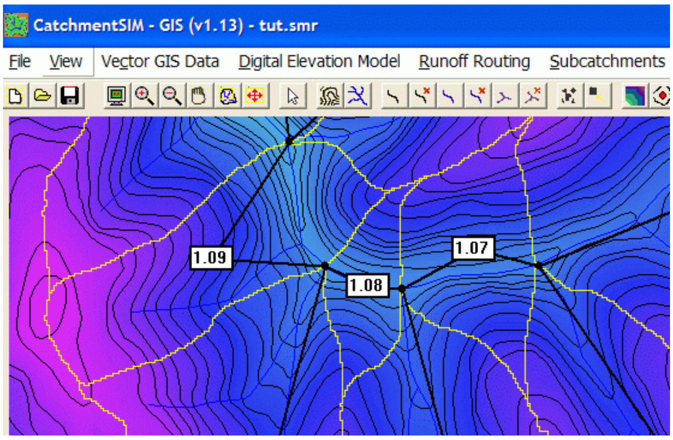


This can be easily fixed by altering the 9.01 outlet. Do this by clicking on subcatchment 9.01 as this is the subcatchment outlet you wish to alter. Add the cell to the west of the outlet, namely (233,165) to the outlet by using the new outlet cell button and typing the row and column value, or selecting *Edit Cells On DEM* and manually clicking on cells to toggle on and off their inclusion in the subcatchment outlet cells. If you choose to use the later technique simply click on the cell next to the outlet cell identified in red (*you may need to zoom further in*) and then click *Finished*.





Once the second cell has been added to the *Edit Subcatchment Outlet* form select *Ok*. Following adjustment of the outlet you will need to reprocess drainage paths to see the effect of your changes. This can be done by reprocessing the entire DEM but to save time it is only necessary to reprocess subcatchment 1.08 (*since it contains the incorrectly assigned cells*). To do this select **Reprocess Subcatchment** from the **Runoff Routing** menu and click on subcatchment 1.08. You should notice that the problem has been fixed and the boundary is now a single line.



Network Arrangement

The subcatchments are automatically arranged in a hydrologic network arrangement. To view this select *Nodal Link Arrangement* in the *View Attributes* form. The subcatchments are labeled, and subcatchment links drawn, in accordance with the options selected in the Project Options form (*accessible through the* **File** *menu*).

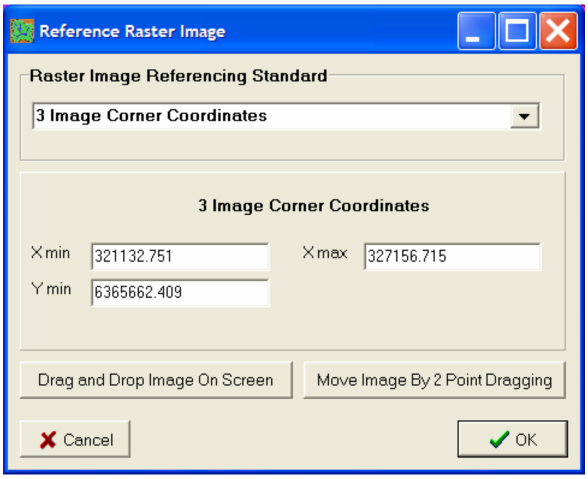
DISPLAY OF EXTERNAL GIS LAYERS

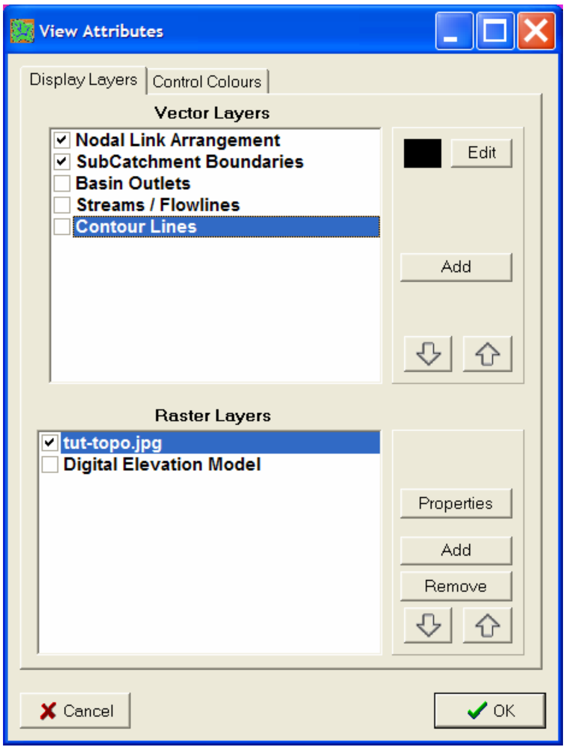
CatchmentSIM supports display of many other vector or raster GIS layers. Examples of this may include displaying a Mid/Mif or ESRI shape file containing road networks or other infrastructure on the screen (*using the Add button in the Vector Layers section of the View Attributes Form*) or insertion of a scanned topographic image (*using the Add button in the Raster Layers section of the View Attributes Form*). A scanned topographic image has been included in the GIS sample data for this purpose. To add this image to your project selected the *Add* button in the *Raster Layers* section of the *View Attributes Form* and select the tut-topo.jpg image. Using the *3 Image Corner Coordinates* referencing standard enter the following coordinates for the image extents:

Xmin: 321132.751

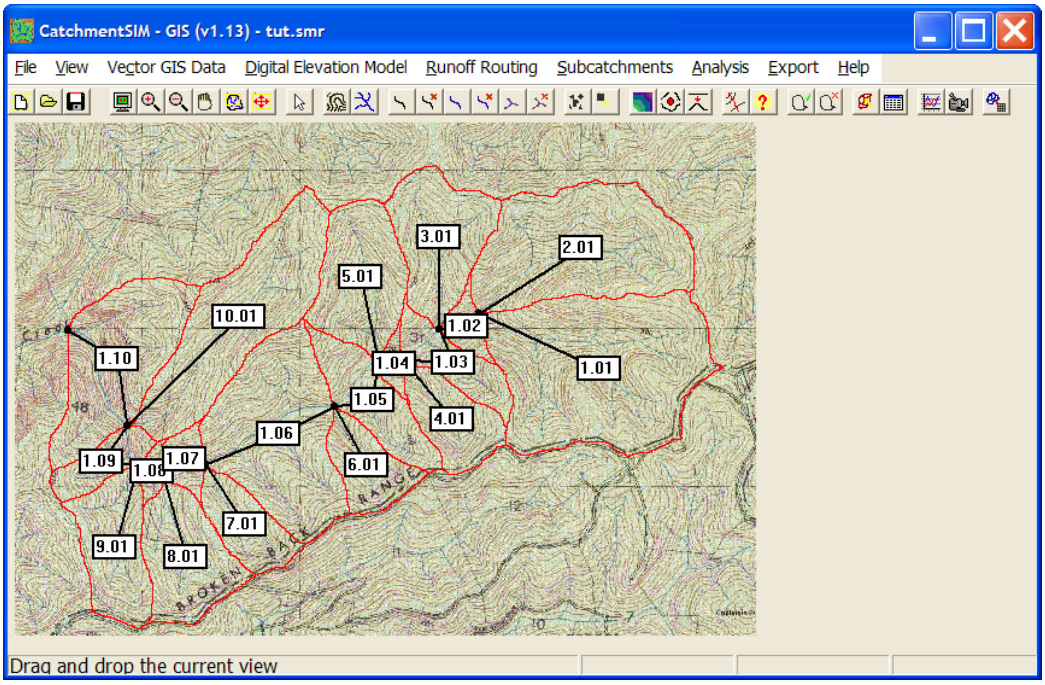
Ymin: 6365662.409

Xmax: 327156.715





By turning off the contour and stream layers in the *View Attributes* form you will be better able to see the subcatchment boundaries superimposed over the scanned topographic image.

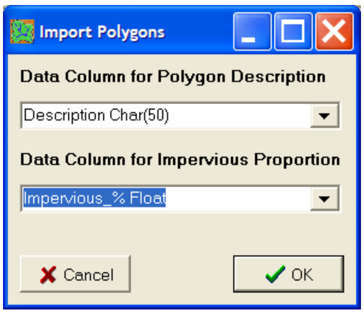


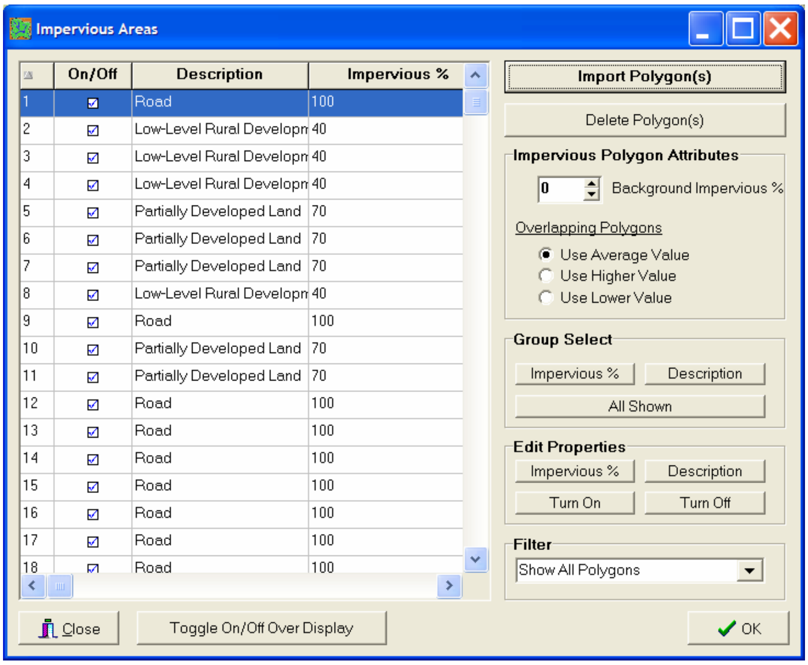
If the coordinates of the raster image extents are unknown then the image can be positioned by clicking a rectangle on screen using the *Drag and Drop Image On Screen* button and then geo-referenced by identifying points on the image and drawing arrows to their corresponding real location using the *Move Image By 2 Point Dragging* button.

IMPERVIOUS AREAS

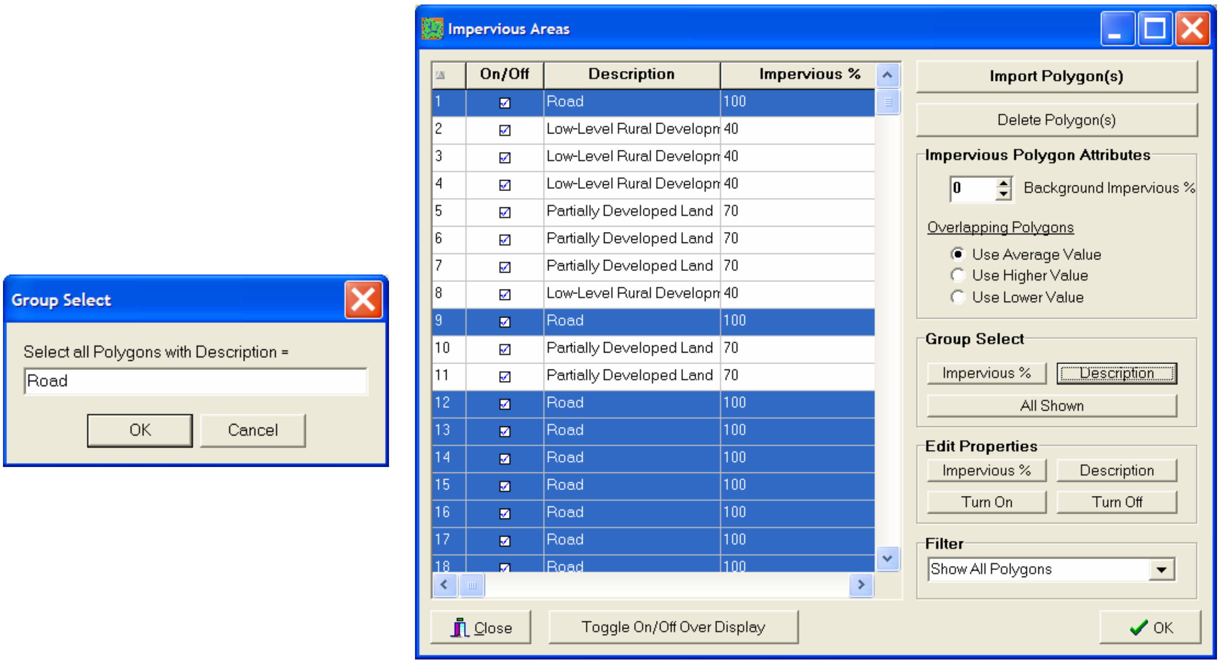
CatchmentSIM also provides a function for users to import polygons that represent impervious or partially impervious areas into a project. Alternatively, these can be drawn directly onto the screen using the **Draw Impervious Area Polygon** menu item from the **Vector GIS Data** menu. CatchmentSIM will accept any type of normal or complex polygon (*such as 'island' polygons, polygons with holes and concave polygons*) and will automatically calculate the impervious proportion for each subcatchment.

For this tutorial, a sample data-set of impervious areas has been included with the GIS data. Select **Impervious Areas** from the **Vector GIS Data** menu and then select **Import Polygon(s)**. Locate and select the file **impervious-areas.mif**. A dialog box will then require you to identify data columns in the GIS data-set that correspond to the polygon description and impervious proportion fields. These can be assigned to '*None'* and entered manually at a later stage, however, this sample data-set includes these attributes. For the polygon description field select the *'Description Char(50)'* data column and for the Impervious Proportion field select the *'Impervious_% Float'* data column and then press *OK*. CatchmentSIM will then import the polygons and update the form's grid accordingly.



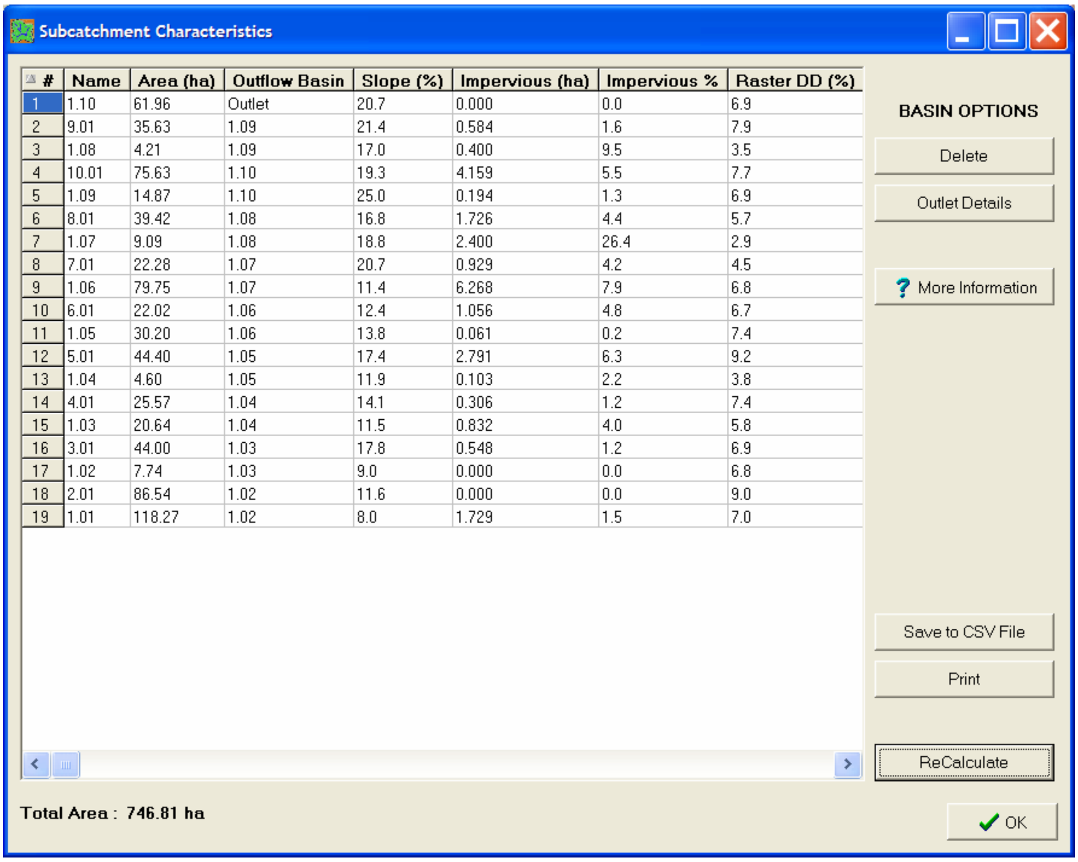


From the *Impervious Areas* form a user can turn polygons on or off and edit their description or impervious proportion attributes. This can be done for single polygons or multiple polygons by using the control or shift keys or the group selection functions. It should also be noted that the polygons will be highlighted in red on the main form in the background when they are selected. The form also includes a filter function and options that dictate the background impervious proportion and control how any overlapping polygons are treated. In the example presented below, polygons have been queried based on their Description equalling "*Road*". These polygons can then be group-edited using the *Edit Properties* buttons.



The simplest method of turning polygons on and off is by clicking the associated checkbox, however, this may be done spatially by selecting the **Toggle On / Off Over Display** button. This will allow a user to turn polygons off and on by simply clicking on them, active polygons will be shown in black while inactive polygons are shown in light grey.

Once you have finished experimenting with these functions, press OK. The impervious areas will then be displayed on the screen and the calculated impervious proportions for each subcatchment will be listed in the *Subcatchment Characteristics* form (*see below*).

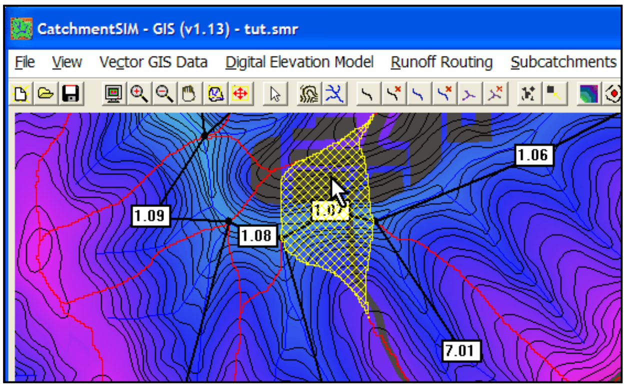


#	Name	Area (ha)	Outflow Basin	Slope (%)	Impervious (ha)	Impervious %	Raster DD (%)
1	1.10	61.96	Outlet	20.7	0.000	0.0	6.9
2	9.01	35.63	1.09	21.4	0.584	1.6	7.9
3	1.08	4.21	1.09	17.0	0.400	9.5	3.5
4	10.01	75.63	1.10	19.3	4.159	5.5	7.7
5	1.09	14.87	1.10	25.0	0.194	1.3	6.9
6	8.01	39.42	1.08	16.8	1.726	4.4	5.7
7	1.07	9.09	1.08	18.8	2.400	26.4	2.9
8	7.01	22.28	1.07	20.7	0.929	4.2	4.5
9	1.06	79.75	1.07	11.4	6.268	7.9	6.8
10	6.01	22.02	1.06	12.4	1.056	4.8	6.7
11	1.05	30.20	1.06	13.8	0.061	0.2	7.4
12	5.01	44.40	1.05	17.4	2.791	6.3	9.2
13	1.04	4.60	1.05	11.9	0.103	2.2	3.8
14	4.01	25.57	1.04	14.1	0.306	1.2	7.4
15	1.03	20.64	1.04	11.5	0.832	4.0	5.8
16	3.01	44.00	1.03	17.8	0.548	1.2	6.9
17	1.02	7.74	1.03	9.0	0.000	0.0	6.8
18	2.01	86.54	1.02	11.6	0.000	0.0	9.0
19	1.01	118.27	1.02	8.0	1.729	1.5	7.0

HYDROLOGIC ANALYSIS

At this stage, you are ready to export the resultant quasi-distributed hydrologic model to a back-end application or export project layers to a GIS application, but there are many other tools in CatchmentSIM which you may like to apply to the catchment beforehand. A range of hydrologic analysis tools are available to assist with gaining a quantitative understanding of the hydrologic properties of the various subcatchments or the catchment as a whole. These include customisable graphs, calculation of common hydrologic properties such as drainage density or bifurcation ratio and dynamic parameter variance animations.

To begin with, a range of available parameters for the subcatchments can be viewed in the *Subcatchment Characteristics* form. This form can be accessed from the **Subcatchments** menu by selecting **Subcatchment Manager**. Alternatively, you can see the highlighted row of this table for a particular subcatchment by selecting **View Subcatchment Attributes** and clicking on the relevant subcatchment (*it will highlight as you scroll the mouse over it*). Some other hydrologic analysis tools are described below:



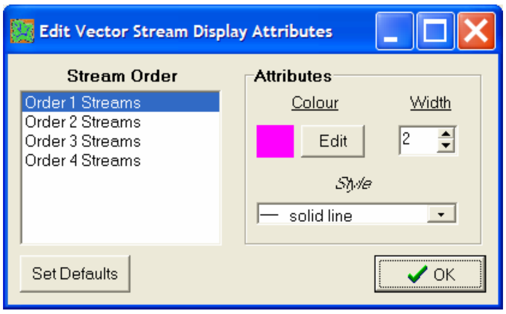
Subcatchment Characteristics

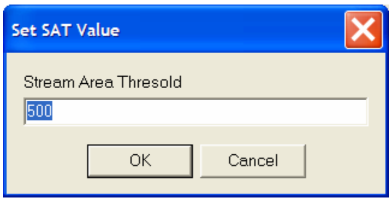
#	Name	Area (ha)	Outflow Basin	Slope (%)	Impervious (ha)
1	1.10	61.96	Outlet	20.7	0.000
2	9.01	35.63	1.09	21.4	0.584
3	1.08	4.21	1.09	17.0	0.400
4	10.01	75.63	1.10	19.3	4.159
5	1.09	14.87	1.10	25.0	0.194
6	8.01	39.42	1.08	16.8	1.726
7	1.07	9.09	1.08	18.8	2.400
8	7.01	22.28	1.07	20.7	0.929
9	1.06	79.75	1.07	11.4	6.268
10	6.01	22.02	1.06	12.4	1.056
11	1.05	30.20	1.06	13.8	0.061

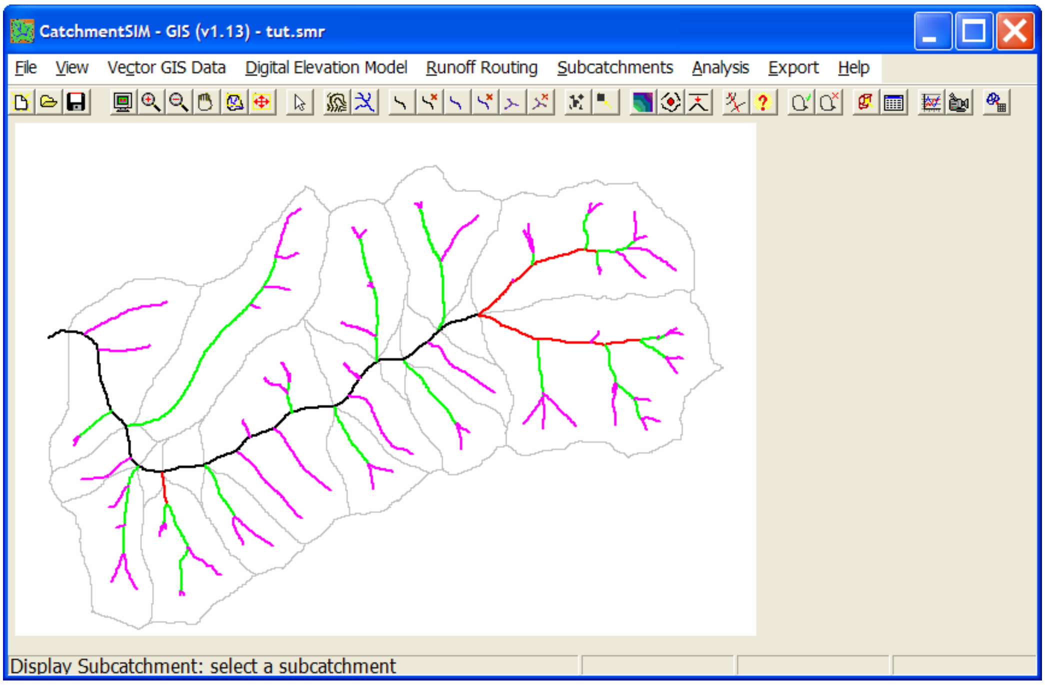
Vector Stream Network

In addition to determining raster stream cells CatchmentSIM also offers a more powerful and hydrologically accurate form of stream network prediction by defining a vector stream network. This is achieved by identifying potential channel heads using the Stream Area Threshold and then generating an intersecting polyline stream network by routing flow from these cells to the catchment outlet. During this process, CatchmentSIM will determine alignments, lengths and stream order values for each predicted stream segment.

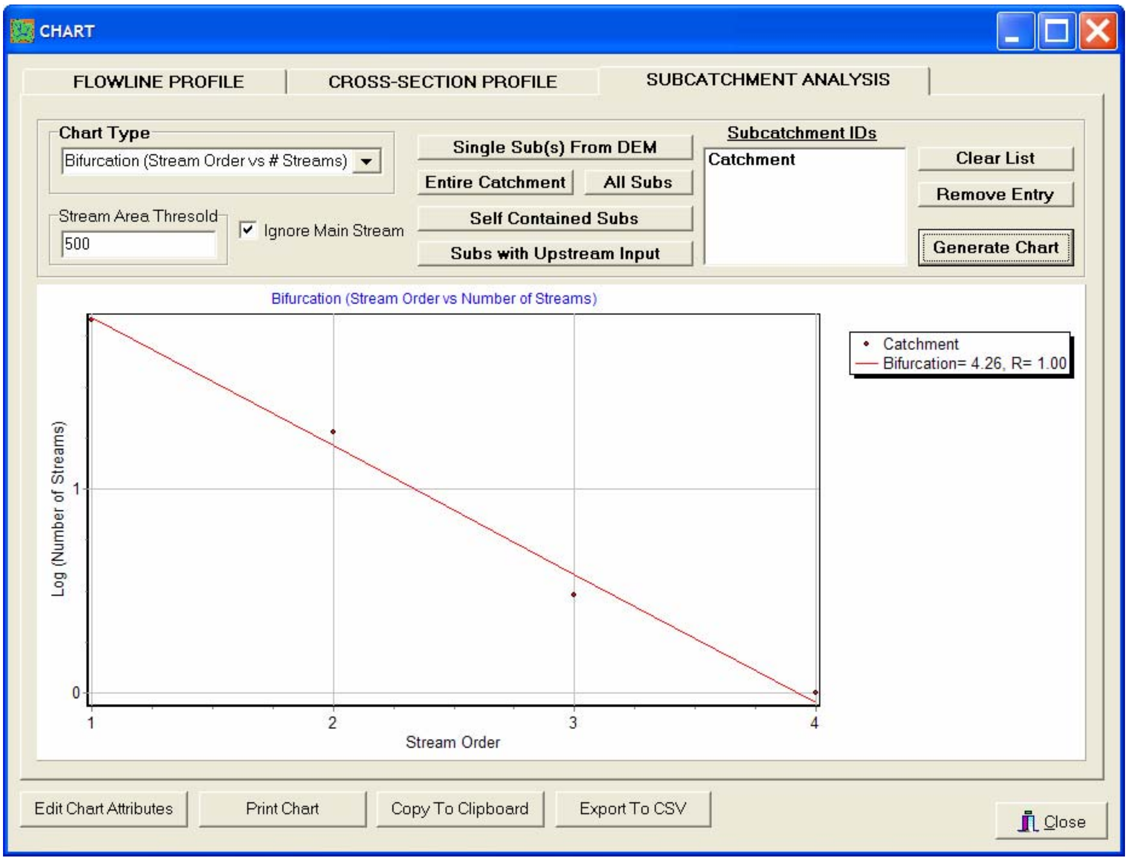
This function can be activated by selecting **Draw Vector Streams** from the **Runoff Routing** menu. The display of this layer can be customised from the *View Attributes Form* by selecting the *Synthetic Streams* row and clicking *Properties*. This will generate a form which will allow you to set a colour, width and line type for different stream order values.







Generating the vector stream network will also allow for determination of Horton drainage density values and Bifurcation ratio values which are displayed in the *Subcatchment Characteristics Form.* Vector stream networks can also be used as the basis for automatic catchment breakup. The bifurcation ratio for the project expressed as a chart is shown below.



Charting

CatchmentSIM includes a range of graphical analysis tools, which can be accessed through the **Analysis** menu by selecting **Graph Wizard**. Samples of these charts include:

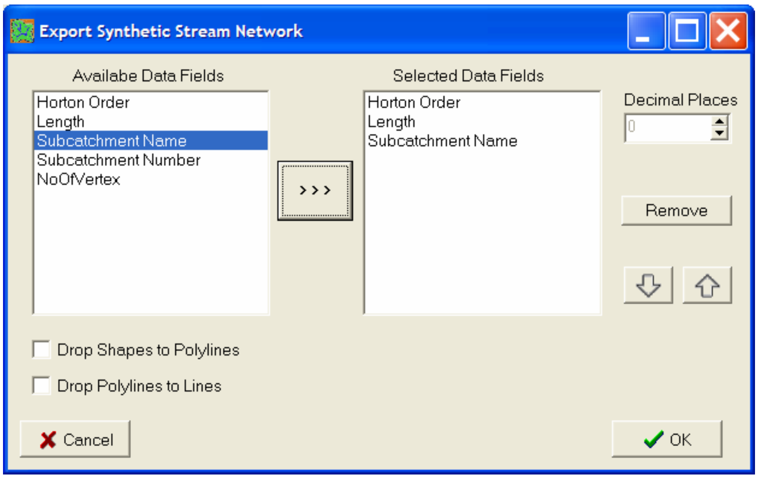
- Longitudinal downslope profile for any cell (*including superimposed average vectored slope*).
- In-stream cell proportion vs overland flow distance.
- Raster drainage density vs Stream Area Threshold (SAT).
- Bifurcation ratio (*Log (number of streams) vs stream order).*
- Cumulative stream length vs stream order (*log / log*).
- Hypsometric curve (*relative height vs relative area*).
- Stream elevation drop scatter charts.
- Bifurcation versus SAT value.

Parameter Variance Animation

CatchmentSIM allows for the development of AVI animation files that illustrate how a particular attribute display will change with the variance of specified parameter(s). This tool can be accessed through the **Create Animation** option under the **Analysis** menu. For example try selecting the *Stream Area Threshold Animation* and loading a *Default Sequence*. Press *Create* and after processing, an animation will be shown that illustrates the effect of varying the SAT value on the raster stream cell display. The animation can be further customised by setting up the current display with the *View Attributes Form* prior to generating the animation. A sample of this animation can be downloaded from the website.

GIS EXPORT

CatchmentSIM allows export of most project data (*visual and tabular*) to external GIS applications. This function can be accessed through the **Export GIS Data** option in the **Export** menu. The following screens will allow you to select which data layers you would like to export and which tabular data you would like to attach to the visual GIS data. CatchmentSIM will then write the GIS data files to enable direct import of this information into another GIS application (*Note: CatchmentSIM exports GIS data as a non-earth projection, as such, depending on the projection of the original source data you may need to specify the data projection when utilising GIS export files from CatchmentSIM*)



HYDROLOGIC MODEL INTEGRATION

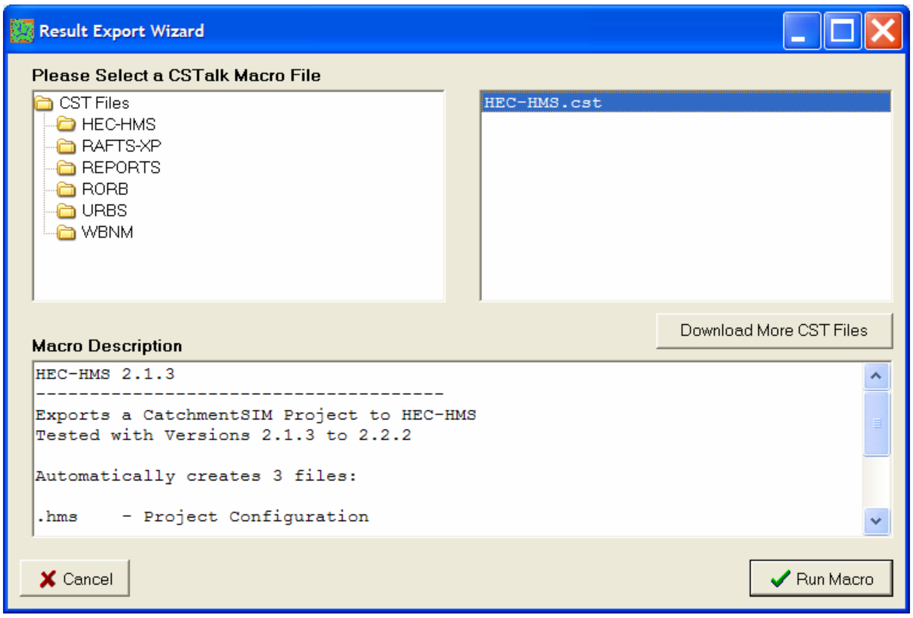
CatchmentSIM provides a powerful method for extracting results and parameters from projects. A flexible macro language is built into the software to allow generation of text or binary files in any desired format. This means CatchmentSIM can be tailored to provide input files for any other hydrologic model. The macro language reads macro templates that can be distributed with the program, downloaded off the web or written by a user. To write your own export macro scripts refer to the CatchmentSIM CSTalk Macro Reference Guide.

Presently, CatchmentSIM integrates directly with several hydrologic models by using CSTalk macro scripts, namely:

- Runoff Analysis & Flow Training Simulation (RAFTS-XP)
- Watershed Bounded Network Model (WBNM)
- RORB
- URBS
- Hydrologic Modelling System (HEC-HMS)
- DRAINS

However, more CSTalk macro scripts are under development, check the website for updates.

To integrate your tutorial project with one of the above modelling systems, select **Result Export Wizard** from the **Result Export** menu. The default path for the macro scripts is indicated in the top left box and any subdirectories may be accessed through this control. The box to the right lists the macro scripts available in the selected directory. Information on each macro script will appear in the bottom box after clicking on a script file.



Select the macro file that corresponds to the desired back-end hydrologic model and click *Run Macro*. After answering any questions the script may generate, you should find that CatchmentSIM has created the file(s) required for integration with the back-end model. For example, in the case of a HEC-HMS export, CatchmentSIM will automatically create 3 files (.hms .basin & .map) which can then be opened up directly from the HEC-HMS software.

CONCLUSION

This tutorial has aimed to give you an introduction to the features of CatchmentSIM. Please feel free to experiment with the many other tools within the program and remember to check the website for software updates.

Feedback, ideas and questions are always appreciated and can be submitted via the website.

APPENDIX B

CSTALK MACRO LANGUAGE GUIDE

CSTALK MACRO LANGUAGE GUIDE

INTRODUCTION

The CSTalk macro language was developed as a component of this research project as a means to enable coupling of CatchmentSIM with other hydrologic and hydraulic computer software. The key objectives in the development of the macro language were functionality, transparency and simplicity. Thus, firstly, the language should be powerful enough to provide coupling with any other programs whether they utilise binary or text files as inputs. Secondly, the language must be text file based and not require special software or compilers. Finally the language must be simple enough to enable users without extensive programming experience to develop CSTalk macro scripts.

This document includes instructions and reference material for writing and editing CSTalk macro scripts for use with CatchmentSIM software. Some of the key uses of CSTalk macro scripts are:

Export of project attributes to 3rd party software

CSTalk macro scripts can be used to create input or auxiliary files for 3rd party software such as other hydrologic modelling packages. Some examples of these software packages are HEC-HMS, WBNM, RORB, URBS, DRAINS and RAFTS-XP for which customised CSTalk macro scripts are included with the CatchmentSIM software.

This allows seamless coupling between CatchmentSIM and other software packages.

Creation of customised report formats

Users may wish to create an in-house report export template using a CSTalk macro script for the purposes of document control and quality assurance.

CSTalk scripts consist of a Header Section and script code. Script code constitutes Procedures, Logical Operators, Dialog Boxes and Variables. These tools, when utilised in combination, provide the flexibility to create output file with almost any type of content and structure.

This document is not intended to be a tutorial or provide comprehensive instructions for beginner macro programmers. Rather, it is a reference guide that lists the available commands and variables in the CSTalk language. For those aiming to learn to write a CSTalk macro script it is recommended that the scripts included with the CatchmentSIM software (*in the CST Files directory*) be studied with reference to this document to help decipher the scripting technique.

HEADER SECTION

The Header section in a CST macro script should consist of information regarding the intended use for the script and other relevant information. It consists of three tags, namely, **MACRO-DESCRIPTION**, **END-MACRO-DESCRIPTION** and **START-SCRIPT**. The first line in a script should be the **MACRO-DESCRIPTION** tag. Text entered between this tag and the **END-MACRO-DESCRIPTION** tag is the Macro Description and will appear in the bottom window of the Result Export Wizard as shown below. On the next line from the **END-MACRO-DESCRIPTION** tag, the **START-SCRIPT** tag should be entered. This designates the start of the script code.

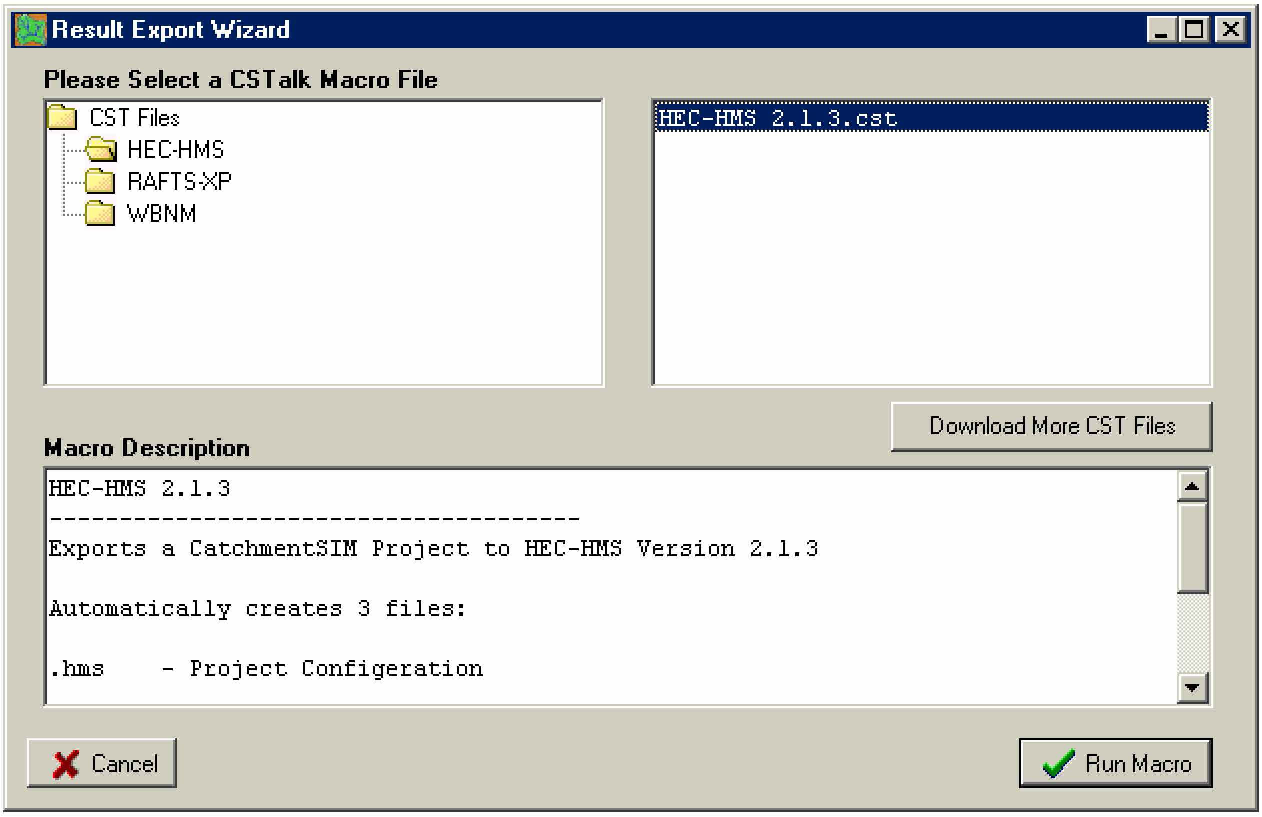
EXAMPLE

```
MACRO-DESCRIPTION
HEC-HMS 2.1.3
-------------------------------------
Exports a CatchmentSIM Project to HEC-HMS Version 2.1.3

Automatically creates 3 files:

.hms    - Project Configuration
.basin  - Basin Data File
.map    - GIS background file

More information about HEC-HMS can be found at:
http://www.hec.usace.army.mil/software/software_distrib/hec-hms/hechmsprogram.html
END-MACRO-DESCRIPTION
START-SCRIPT
```



SCRIPT STRUCTURE

When CatchmentSIM reads a macro script (*all text after the START-SCRIPT tag*) it ignores all space characters except those between double quotation marks (" "). As a result, blank lines or large spaces can be left to help make code more easily readable by another person.

Comments can also be included in the text to ease understanding of the script code or flag areas for future consideration. Comments must be enclosed by curly brackets **{ }**.

It is standard programming practice to indent commands that are embedded within logical operators (*eg., LOOP or IF structures*). This further aids to enhance the readability of macro scripts and helps to ensure that right parenthesis of the logical operators are not omitted (*these can be hard errors to track down*). An example of the indentation programming practice is shown below (*comments are shown in blue*).

EXAMPLE

```
LOOP(i|1|%Project.DEMRows|
   LOOP(j|1|%Project.DEMColumns|
      {script commands}
   ) {end j loop}
) {end i loop}
```

CSTALK PROCEDURES

CSTalk procedures are commands that undertake specific tasks using a range of supplied parameters. These parameters (*shown in red*) may take the form of specific values or alternatively, user variables or project variables that contain data of an appropriate data type.

If a parameter is entered manually (ie., not wrapped in a user variable or project variable) then non-numerical parameters should be enclosed in quotation marks (""). This applies in all situation except specific program tags such as **L** and **R** if the justification parameter of the **FTXT** procedure, **ASCII**, **BINARY** in the

StartPrintToFile procedure etc. These tags are identified in the *Accepted Values* column in the parameter description tables.

Text Output Procedures

TXT (*Text / Value*)

The **TXT** procedure writes un-formatted information (*Text / Value*) to a text-file.

Eg., TXT("My Customised CatchmentSIM Report")

FTXT (*Justification* , *Offset* , *Multiplier* , *Decimal Places* , *Text / Value*)

The **FTXT** procedure writes formatted information (*Text / Value*) to a text-file in accordance with the following parameters.

Parameter	Description	Accepted Values / Data Type
Justification	Align the left or right side of the text with the offset value. This parameter can be left blank, in which case text will be printed at the current file position.	**L** (left), **R** (right) or blank
Offset	Number of characters from start of line with which to align text. This parameter is ignored if Justification parameter is left blank.	Integer
Multiplier	Factor to multiply numerical values.	Decimal
Decimal Places	Number of decimal places with which to write numerical values.	Integer

Eg., FTXT(L,20,0.0001,2,%SubCatchment[i].Area)

This command will write the area of subcatchment number *i* to the text-file on the current line aligning the left side of the text with the 20th character from the start of the line. The default units for this project variable are m^2 however, the value will be multiplied by 0.0001 (*ie., converted to hectares*) and written in the text-file to 2 decimal places.

Semi-Colon (;)

The '**;**' symbol will begin a new line in the text-file.

1.1.1 Binary Output Procedures

BINWR (*Write As* , *Bytes To Write* , *Text / Value*)

The **BINWR** procedure writes data to a binary file. The data (*Text / Value*) is written according to the data type indicated in the *Write As* parameter and in the case of a string (*text*) the program will write as many bytes from the text as indicated in the *Bytes To Write* parameter.

Parameter	Description	Accepted Values / Data Type
Write As	Designates the data format to write. Will generate an error if the *Text / Value* is not found to be compatible with this data format.	**INTEGER** : Writes *Text / Value as a* **4 byte** integer **SINGLE**: Writes *Text / Value as a* **4 byte** single precision decimal (7-8 significant figures) **DOUBLE**: Writes *Text / Value as a* **8 byte** double precision decimal (15-16 significant figures) **EXTENDED**: Writes *Text / Value as a* **10 byte** extended precision decimal (19-20 significant figures) **BOOLEAN**: Writes *Text / Value as a* **4 byte** boolean (ie., True / False) **STRING**: Writes *Text / Value as a* string variable, writes *Bytes To Write* bytes to the text file
Bytes To Write	Only used if Write As = **STRING**. Designates the number of bytes in string to write. If Bytes To Write > size of string then remainder of bytes written are space character. If Bytes To Write < size of string then the string is trimmed to size of Bytes To Write and written to file.	Integer

SizeOfString (*Result Variable* , *String / String Variable*)

The **SizeOfString** procedure determines the number of bytes required to completely write a *String / String Variable* to a binary file and stores the result in a user variable (*Result Variable*).

EXAMPLE

```
StartPrintToFile(&Binary_File,BINARY,WINDOWS,OVERWRITE)

   SizeOfString(&String_Size, %Project.Title)
   BINWR(INTEGER, {not required since NOT STRING}, &String_Size)
   BINWR(STRING, &String_Size, %Project.Title)

EndPrintToFile(&Binary_File)
```

This example opens a binary file for write access and writes the length of the string type project variable %Project.Title as an integer followed by the entire string. This example is relevant because it is often necessary when writing strings to binary files to write the length of the string to file as an integer prior to writing the string. This may be done to ensure when the intended application reads the file, it can first read the string length in order to know the number of bytes it should read into the string variable.

String Editing Procedures

Combine (*Result Variable* , *Text / Value 1* , *Text / Value 2*)

The **Combine** procedure will concatenate two text or numerical values (*Text / Value 1 & 2*) into one and store the result in a user variable (*Result Variable*).

ChangeExtension (*Result Variable* , *Old Path* , *New Extension*)

The **ChangeExtension** procedure will replace the extension of *Old Path* with the extension given in *New Extension* and store the result in a user variable (*Result Variable*). The *New Extension* should include the period / full stop symbol '.'.

Eg., ChangeExtension(&New_FileName, %Project.PathAndFileName, '.bmp')

GetFileNameFromPath (*Result Variable* , *Path* , *Keep Extension*)

The **GetFileNameFromPath** procedure strips the relevant section of a file path to reveal the filename in accordance with the parameter listed below and stores the result in a user variable (*Result Variable*).

Parameter	Description	Accepted Values / Data Type
Keep Extension	Indicates whether to retain the path extension in the *Result Variable* or not.	**WITH** or **WITHOUT**

AssignVariable (*Result Variable* , *Variable*)

The AssignVariable procedure simply assigns a value from a project or user variable (*Variable*) to a user variable (*Result Variable*).

File Handling

StartPrintToFile (*File Path* , *File Type* , *Platform* , *Write Style*)

The **StartPrintToFile** procedure opens a file designated by *File Path* for writing in accordance with the parameters listed below. A **StartPrintToFile** procedure must have a corresponding **EndPrintToFile** command further down the command sequence.

Parameter	Description	Accepted Values / Data Type
File Path	The full path of the output file to write to.	Text
File Type	Indicates whether to write to a text or binary file type.	**ASCII** or **BINARY**
Platform	The platform of the applications intended for use with the output file (only relevant when File Type = **ASCII**)	**WINDOWS** or **UNIX**
Write Style	In the case that the file already exists, indicates whether to overwrite or append the file.	**OVERWRITE** or **APPEND**

EXAMPLE

```
SaveDialogBox(&HMSFile,"HEC-HMS Project (*.hms)",".hms","")

StartPrintToFile(&HMSFile,ASCII,WINDOWS,OVERWRITE)

 {Text File Export Procedures}

EndPrintToFile(&HMSFile)
```

EndPrintToFile (*File Path*)

The **EndPrintToFile** procedure simply closes a file that has previously been opened using a **StartPrintToFile** procedure.

Image Handling

ExportBackgroundPicture (*File Path (.bmp)*)

The **ExportBackgroundPicture** procedure writes a Windows bitmap image (.bmp) to a file as designated by *File Path*. To ensure the image is opened properly with other applications, the user should ensure that the *File Path* variable has the extension '.bmp'.

The image exported is the current view in the CatchmentSIM project. That is, if the current view is zoomed in to small area then this image will be exported. In this manner any image generated during operation of CatchmentSIM can be exported to an image file. The coordinates for the exported image are stored in the *%BackgroundPicture.MaxEasting*, *%BackgroundPicture.MaxNorthing*, *%BackgroundPicture.MinEasting* and *%BackgroundPicture.MinNorthing* project variables.

EXAMPLE

```
YesNoBox(&B_Image,"Would you like to export a background graphic","Background Image")

IF(&B_Image|=|True|
  SaveDialogBox(&BMPFile,"Windows Bitmap (*.bmp)",".bmp","")
  ExportBackgroundPicture(&BMPFile)
)
```

LOGICAL OPERATORS

LOOP (*Loop Letter* | *Start At* | *End At* | *Loop Procedures*)

The **LOOP** operator repeatedly processes a designated command sequence a set number of times. On each loop of the command sequence any occurrences of the loop letter as a embedded parameter in the loop procedures are substituted with the current iteration of the loop.

Parameter	**Description**	**Accepted Values / Data Type**
Loop Letter	Designates the letter to substitute within the loop procedures with the current loop iteration.	Any single letter, traditionally i, j, k etc
Start At	Integer value for first iteration of loop.	Integer
End At	Integer value for final loop iteration.	Integer
Loop Procedures	Any number of embedded procedures or further logical operators designed for repetition within loop.	

EXAMPLE

```
LOOP(i|1|%Catchment.NumberOfSubCatchments|
  TXT("Subbasin:")
  FTXT(L,10,1,0,%SubCatchment[i].Name);
)
```

This loop example will repeat three commands for every subcatchment within the current project. These commands are:

1. Write the un-formatted text *Subbasin:*
2. Write the name of the subcatchment with ID value equal to the current iteration of the loop; and,
3. Start a new line (*indicated by the semi-colon ';' command*)

The right bracket on the bottom line is the partner of the left bracket of the LOOP operator and is necessary to designate the end of the loop procedures.

IF (*Test Variable* | *Test Type* | *Test Against* | *Success Procedures*)

The **IF** operator will process or omit a designated command sequence based on application of a logical test. The test compares two parameters, *Test Variable* and *Test Against* with reference to a *Test Type* as described in the following.

Parameter	Description	Accepted Values / Data Type
Test Variable	Designates the variable or value with which to compare with the Test Against value.	Any numeric or string value.
Test Type	Type of test to conduct.	**=** : IF equal to **<** : IF lesser than **>** : IF greater **=<** : IF lesser or equal to **>=** : IF greater or equal to **<>** : IF not equal to
Test Against	Variable or value to be tested against Test Variable using Test Type.	Any numeric or string value.
Success Procedures	Any number of embedded procedures or further logical operators designed for processing after application of a successful test.	

EXAMPLE

```
LOOP(i|1|%Catchment.NumberOfSubCatchments|
 IF(%SubCatchment[i].CatchmentOutlet|=|False|
   TXT("Downstream Subcatchment:")
   FTXT(L,25,1,0,%SubCatchment[i].DownstreamSubCatchmentName);
  )
)
```

This example loops through all the subcatchments in the current project and for each subcatchment the following IF test is initiated:

IF the *Catchment Outlet* project variable relating to the current subcatchment iteration in the loop is equal to (*Test Type*) the value False (*Test Against*) then the embedded IF procedures are processed, otherwise they are not processed.

This sample code is designed to ensure that the downstream subcatchment name is only written for subcatchments that have a downstream subcatchment since the catchment outlet subcatchment will not have a downstream subcatchment.

WHILE (*Test Variable* | *Test Type* | *Test Against* | *Success Procedures*)

The **WHILE** operator will process a designated command sequence continuously until a designated test is no longer successful. The test parameters (*Test Variable, Test Type* and *Test Against*) are used identically to those described in the **IF** operator. If the test fails on the first iteration, the *Success Procedures* will not be processed.

For a **WHILE** operator to be of use the *Test Variable* must be a user variable and must be re-assigned during the course of the *Success Procedures*. Otherwise, the loop will either never process or process endlessly.

EXAMPLE

```
WHILE(&Continue_Processing|=|True|
 {process commands}
   IF( {test for break while loop} |=|True|
     AssignVariable(&Continue_Processing,False)
   )
)
```

This example will continuously processes a set of commands (*process commands*) until a designated test is passed (*test for break while loop*) and will then assign a user variable (*&Continue_Processing*) a value of false, which will inturn cause the **WHILE** loop to terminate.

MATHEMATICAL FUNCTIONS

Various mathematical routines can be incorporated into CSTalk macro scripts to help perform certain user functions.

Simple Mathematical Operators

Simple mathematical operators include the multiplication (*), division (/), addition (+) and subtraction (-) functions. These can be implemented within parameters of virtually any procedure or logical operator that is expecting a numerical input. An example are shown below.

EXAMPLE

```
GetArrayLength(&Array_Length,&DynamicArray)

AssignVariable(&DynamicArray[&Array_Length+1],4+6-3)
```

This example reads the length of a previously declared user array variable. The array is then extended by one position (*by assigning to its length + 1*) and a value of 7 (4+6-3) is then assigned to the last array position.

DIALOG BOXES

A number of dialog boxes can be triggered by commands within macro scripts. These may be used to get text or numerical information from a user, select a location to save a file, or to display a message to the user. These dialog box triggers are described in the following section.

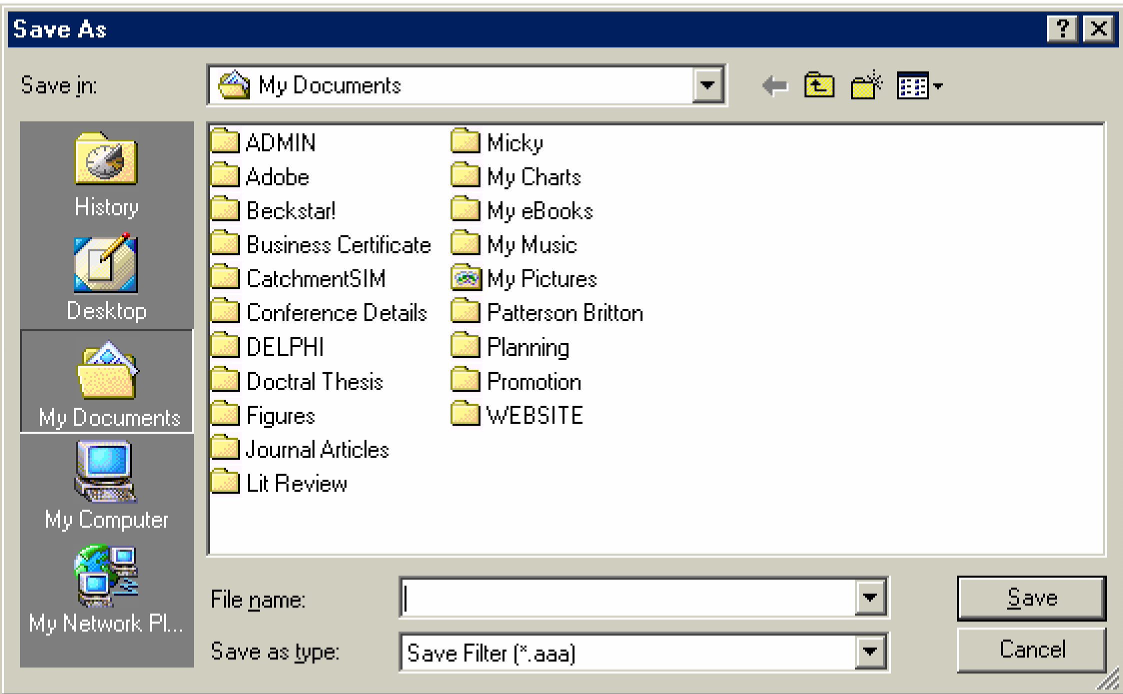
MessageBox (*Message Text* , *Dialog Box Title*)

The **MessageBox** command simply displays information to the user. The message text may take the form of pre-defined text or display a project variable or user variable's value.

SaveDialogBox (*Result Variable* , *Save Filter* , *Add Extension*, *Default Filename*)

The **SaveDialogBox** command triggers a traditional Windows 'Save As' dialog box as pictured below. The user may navigate to a directory of choice and enter their desired filename. Once the Save button is clicked the resultant complete file path is stored in the *Result Variable*. This user variable can then be used as a input parameter for another procedure such as **StartPrintToFile**.

The *Save Filter* text indicates the file type that the user is saving and is displayed in the Save as type combobox. The *Add Extension* variable ensures that the extension entered is added onto the filename (*if not already present*).



EXAMPLE

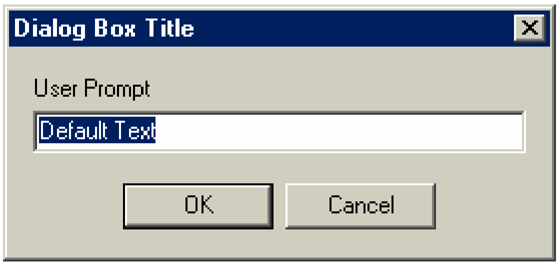
SaveDialogBox(&HMSFile,"HEC-HMS Project (*.hms)",".hms","")

This example will bring up the save dialog box with *HEC-HMS Project (*.hms)* written in the Save as type combobox and will ensure the complete path that is saved to the user variable &HMSFile has the extension .hms.

InputBox (*Result Variable* , *User Prompt* , *Dialog Box Title* , *Default Text*)

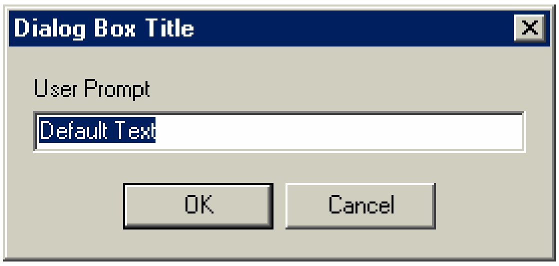
The **InputBox** command triggers a dialog box that request data from the user. If the user chooses the Cancel button, the *Default Text* is stored in the *Result Variable*. If the user chooses the OK button, the user entered text is stored in the *Result Variable*.

An **InputBox** should be used when the script author wishes to use a default value when the user chooses the Cancel button (*or presses Esc*) to exit the dialog. If the script should abort when Cancel is selected then the **InputQueryBox** should be used instead.



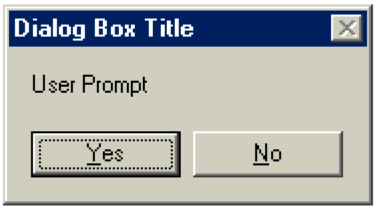
InputQueryBox (*Result Variable* , *User Prompt* , *Dialog Box Title* , *Default Text*)

The **InputQueryBox** operates similarly to the **InputBox**, however, selecting Cancel in an **InputQueryBox** will abort the script operation whereas this action will simply store the default text in the *Result Variable* in the case of an **InputBox**.



YesNoBox (*Result Variable* , *User Prompt* , *Dialog Box Title*)

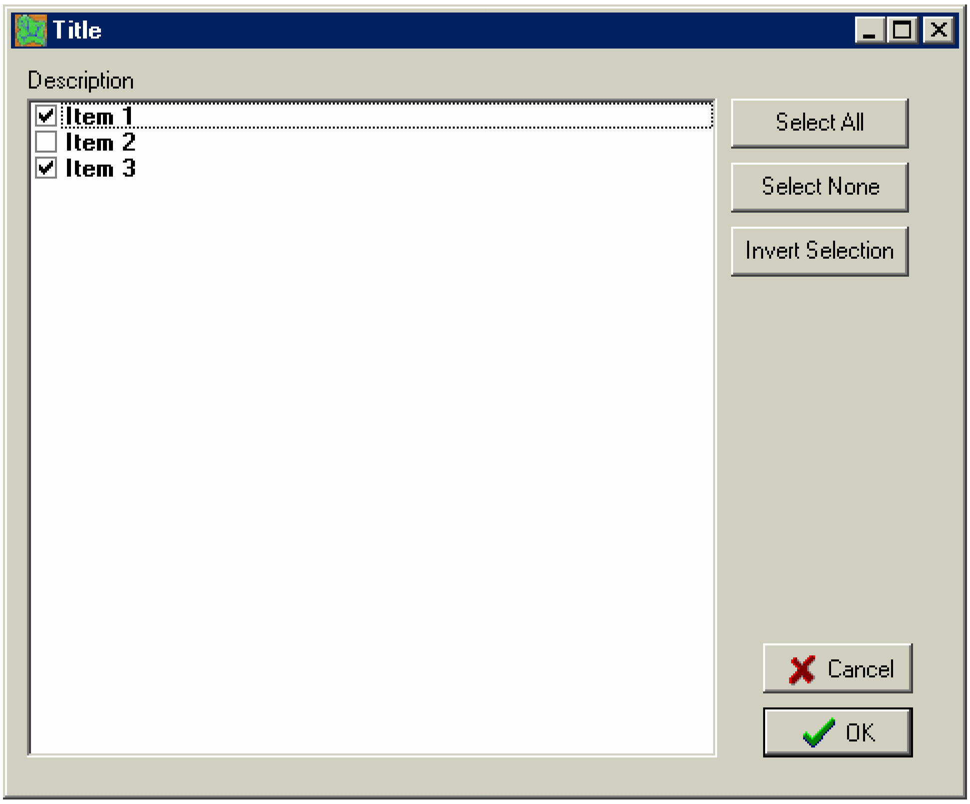
The **YesNoBox** command triggers a dialog box that presents the user with a yes or no button in response to a *User Prompt* message. If the user selects the Yes button then 'True' is stored in the *Result Variable* otherwise 'False' is stored in the *Result Variable*.



Check List Box

SetupCheckListBox (*Description* , *Title*)
AddCheckListBoxItem (*Item Description* , Item Checked)
DisplayCheckListBox (*Array Type User Variable*)

The 3 procedures listed above govern the use of Check List Boxes in CST Macro Scripts. **SetupCheckListBox** initiates the checklist box and sets the description label and title. **AddCheckListBoxItem** can be called any number of times to add an item (*Item Description*) and check or do not check the associated check box in accordance with the True / False type variable in *Item Checked*. **DisplayCheckListBox** designated the end of addition of items and will display the Check List Box. After the user selects OK the *Item Description(s)* that were checked are stored in the *Array Type User Variable*.



EXAMPLE

```
SetupCheckListBox("Description","Title")

AddCheckListBoxItem("Item 1",True)
AddCheckListBoxItem("Item 2",False)
AddCheckListBoxItem("Item 3",True)

DisplayCheckListBox(&ArrayCLBResults)
```

This example was the code used to generate the screen capture illustrated above. The **DisplayCheckListBox** procedure would have created the array variable *&ArrayCLBResults*, set its length to two and stored *Item 1* and *Item 3* in the array since these were the items that were checked. However, the user could have changed the items that were checked before clicking OK and this would effect the length and content of the *&ArrayCLBResults* array variable.

CSTALK VARIABLES

User Variables

User variables are variables that are setup by the script author to hold values from other procedures or project variables. In particular, all the *Result Variable* fields in the CSTalk procedures listed in **Section 0** need to hold a reference to a user variable.

All user variables must begin with the '**&**´ symbol. User variables can be single value user variables, eg., *&Value* or array variables such as *&ArrayValues[0]*, *&ArrayValues[1]*, *&ArrayValues[2]* etc. These are described in the following sections.

Single Value User Variables

User variables do not need to be declared and can be setup on the fly.

EXAMPLE

```
SaveDialogBox(&HMSFile,"HEC-HMS Project (*.hms)",".hms","")

StartPrintToFile(&HMSFile,ASCII,WINDOWS,OVERWRITE)
   {Text Output Files}
EndPrintToFile(&HMSFile)
```

The &HMSFile user variable has been initialised by simply placing it in the *Result Variable* field of the **SaveDialogBox** and was then used in the **StartPrintToFile** and **EndPrintToFile** procedures.

Array Type User Variables

Array type user variables store any number of values in a list. To access an array value at a certain position the terminology &Array_Variable_Name[*Array_Position (integer)*] should be used. Errors will be generated if the *Array_Position* is outside of the range of values in the array or if the &*Array_Variable_Name* user variable is not found.

To help trace typographic errors, array type user variable must be initialised using the **SetArrayLength** procedure. Array initialisation takes the form of **SetArrayLength**(*&ArrayVariable,0).* Array lengths are automatically adjusted to accommodate assignment of array position values. For example, if an array has a current length of 2 and the procedure **AssignVariable**(*&ArrayVariable[6],%Subcatchment[1].Area)* is called then the array length will be extended to six, positions 3-5 will be left empty and position 6 will hold the area of subcatchment 1. More details regarding array procedures are given below.

GetArrayLength (***Result Variable*** **,** ***Array Type User Variable*** ***)***

Returns the length of the *Array Type User Variable* as an integer in the *Result Variable*.

SetArrayLength (***Array Type User Variable*** **,** ***New Length*** ***)***

Sets the length of the *Array Type User Variable* to *New Length*. This can be used to initialise, extend or shorten an array. For example to delete the last two entries in an array the following code could be used.

GetArrayLength(&ArrayLength,&ArrayVariable)

SetArrayLength(&ArrayVariable,&ArrayLength-2)

Project Variables

Project variables are the building blocks of the CSTalk macro language. These variables allow a script to access almost any information regarding the current CatchmentSIM project. Once this information has been extracted from CatchmentSIM via the appropriate project variable it can be used in a logical operator or written to an output file.

All project variables must begin with the percentage symbol prefix '**%**'. Project variable are broken into a number of categories and subcategories which are separated by the period / full stop symbol '**.**' . That is, subcategories and their associated project variables must be accessed through their parent category. The major project variable categories are:

- **Project**
- **Catchment**
- **SubCatchment**
- **Junction**
- **DEMPixel**
- **Impervious Areas**
- **Synthetic Streams**
- **ContourData**
- **StreamData**
- **BackgroundImage**
- **DateTime**

Project Variables

The following project variables relate to the *Project* variable category. They access information regarding the CatchmentSIM project.

These project variables must all be prefixed with **%Project.** eg., *%Project.Title*.

PROJECT VARIABLE *(%Project.)*	DESCRIPTION	OUTPUT TYPE	UNITS
Title	Project Title entered at project setup	Text	
Organisation	Organisation entered at project setup	Text	
CreatedBy	Text entered in 'Created By' box at project setup	Text	
OtherInformation	Text entered in 'Other Information' box at project setup	Text	
PathAndFileName	Full path and filename of project at time of export (eg., c:\CatchmentSIM\demo.smr)	Text	
FileName	Filename of project at time of export (eg., demo.smr)	Text	
ProjectMaxEasting	Easting of most eastward point in project (as entered in project setup)	decimal	user coordinate
ProjectMaxNorthing	Northing of most northward point in project (as entered in project setup)	decimal	user coordinate
ProjectMinEasting	Easting of most westward point in project (as entered in project setup)	decimal	user coordinate
ProjectMinNorthing	Northing of most southward point in project (as entered in project setup)	decimal	user coordinate
DEMMaxEasting	Easting of most eastward point in DEM (as entered in DEM setup)	decimal	user coordinate
DEMMaxNorthing	Northing of most northward point in DEM (as entered in DEM setup)	decimal	user coordinate
DEMMinEasting	Easting of most westward point in DEM (as entered in DEM setup)	decimal	user coordinate
DEMMinNorthing	Northing of most southward point in DEM (as entered in DEM setup)	decimal	user coordinate
PixelArea	Area of an individual pixel	decimal	m^2
PixelWidth	Width of an individual pixel (easting)	decimal	m
PixelHeight	Height of an individual pixel (northing)	decimal	m
DEMRows	Number of rows in DEM.	integer	
DEMColumns	Number of columns in DEM.	integer	

Catchment Variables

The following project variables relate to the Catchment variable category. They refer to statistics and values for the whole catchment, ie., the collection of all subcatchments.

These project variables must all be prefixed with **%Catchment.** eg., *%Catchment.CatchmentArea*.

PROJECT VARIABLE (*%Catchment.)*	DESCRIPTION	OUTPUT TYPE	UNITS
AverageSubCatchmentArea	Average area of all subcatchments	decimal	m^2
AverageSubCatchmentVectoredSlope	Average of average vectored slope for each subcatchment	decimal	m/m
AverageVectoredSlope	Average vectored slope for catchment	decimal	m/m
BifurcationRatio	Average bifurcation for catchment	decimal	
CatchmentArea	Total area of all subcatchments.	decimal	m^2
HortonDrainageDensity	Horton drainage density for catchment	decimal	km/km^2
MainStreamLength	Length of main stream within catchment	decimal	m
MainStreamOriginPixelColumn	Origin pixel column of main stream within catchment	integer	
MainStreamOriginPixelRow	Origin pixel row of main stream within catchment	integer	
MainStreamSlope	Slope of main stream within catchment	decimal	m/m
MaxNetworkDepth	Maximum number of subcatchments that a pixel flow path may traverse	integer	
MaxProcessingOrder	Maximum processing order (should equal number of subcatchments in fully connected network)	integer	
MaxStreamOrder	Maximum Horton stream order for catchment	integer	
NumberOfJunctions	Total number of junctions	integer	
NumberOfPixels	Number of pixels within	integer	

PROJECT VARIABLE (%*Catchment.)*	DESCRIPTION	OUTPUT TYPE	UNITS
	subcatchment.		
NumberOfSelfContainedSubCatchments	Total number of subcatchments without upstream input	integer	
NumberOfSubCatchments	Total number of subcatchments.	integer	
NumberOfThroughFlowSubCatchments	Total number of subcatchments with upstream input.	integer	
RasterDrainageDensity	Raster drainage density for catchment	decimal	m^2/m^2
StDevSubCatchmentArea	Standard deviation of subcatchment areas	decimal	m^2

Subcatchment Variables

The following project variables relate to the *Subcatchment* variable category. They refer to statistics and values for an individual subcatchment which is identified by the integer value referenced in the square brackets following the *%SubCatchment* keyword.

These project variables must all be prefixed with **%SubCatchment[i].** Where ***i*** is an integer, integer type project or user variable or loop substitution letter. eg., *%Subcatchment[i].Name*.

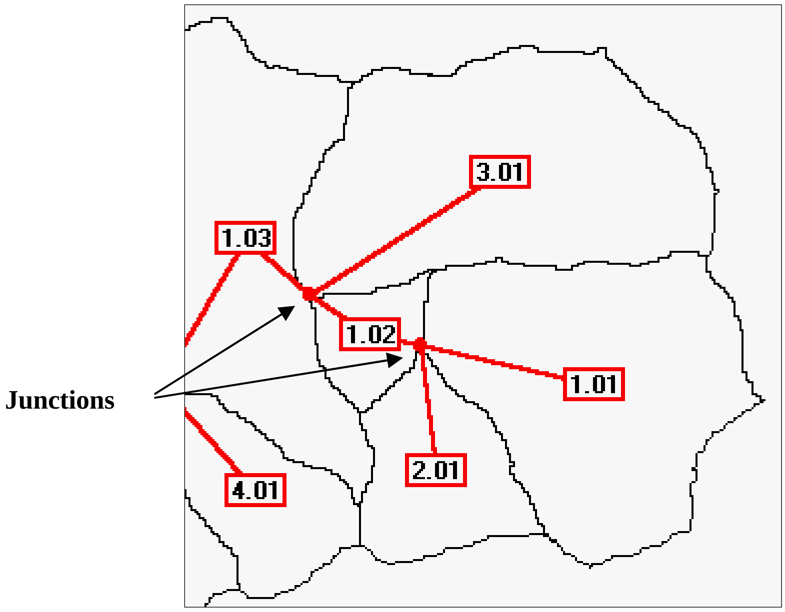
PROJECT VARIABLE (*%SubCatchment[i].*)	DESCRIPTION	OUTPUT TYPE	UNITS
Name	Subcatchment label	text	
Area	Subcatchment area	decimal	m^2
TotalContributingArea	Area of subcatchment and all upstream subcatchments	decimal	m^2
MaxEasting	Easting of most eastward point	decimal	user coordinate
MaxNorthing	Northing of most northward point	decimal	user coordinate
MinEasting	Easting of most westward point	decimal	user coordinate
MinNorthing	Northing of most southward point	decimal	user coordinate
CentroidEasting	Easting of subcatchment centroid	decimal	user coordinate
CentroidNorthing	Northing of subcatchment centroid	decimal	user coordinate
OutletCentroidEasting	Easting of subcatchment outlet	decimal	user coordinate
OutletCentroidNorthing	Northing of subcatchment outlet	decimal	user coordinate
MainStreamSlope	Slope of main stream segment within this subcatchment	decimal	m/m
MainStreamLength	Length of main stream segment within this subcatchment	decimal	m
MainStreamOriginPixelRow	Origin pixel row within this subcatchment for main stream	integer	

PROJECT VARIABLE *(%SubCatchment[i].)*	DESCRIPTION	OUTPUT TYPE	UNITS
	segment within this subcatchment		
MainStreamOriginPixelColumn	Origin pixel column within this subcatchment for main stream segment within this subcatchment	integer	
PerimeterLength	Length of subcatchment perimeter	decimal	m
DownstreamSubCatchmentName	Label of immediate downstream subcatchment	text	
DownstreamSubCatchmentNumber	Subcatchment ID number for immediate downstream subcatchment	integer	
NumberOfUpstreamSubCatchments	Quantity of immediate upstream subcatchment(s)	integer	
UpstreamSubCatchment[j]	Subcatchment ID number of immediate upstream subcatchment 'j' (ie., there may be more than one upstream subcatchment)	integer	
NetworkDepth	Maximum number of subcatchments a flow path may traverse to reach outlet of this subcatchment	integer	
Shape	Shape coefficient (Area / (Perimeter Length) ^{2})	decimal	m^2/m^2
NumberOfPixels	Number of pixels in this subcatchment	integer	
AverageVectoredSlope	Average vectored slope of this subcatchment	decimal	m/m
ImperviousProportion	Proportion of subcatchment that is 100% impervious to infiltration	decimal	m^2/m^2
ImperviousArea	Area of subcatchment that is 100% impervious to infiltration	decimal	m^2
NonImperviousArea	Area of subcatchment that is 0% impervious to infiltration	decimal	m^2
RasterDrainageDensity	Raster drainage density of subcatchment	decimal	m^2/m^2
HortonDrainageDensity	Horton drainage density of subcatchment (vector synthetic stream length / subcatchment area)	decimal	km/km^2
BifurcationRatio	Bifurcation ratio of subcatchment (gradient of line of best fit - stream order vs log(number of streams))	decimal	
DownstreamJunctionNumber	Junction ID number for junction at this subcatchment outlet	integer	

PROJECT VARIABLE *(%SubCatchment[i].)*	DESCRIPTION	OUTPUT TYPE	UNITS
ProcessingOrder	Position of subcatchment 'i' in a list where each subcatchments appear earlier than all its downstream subcatchments. That is, flow from a subcatchment will not enter any subcatchment with a lower processing order.	integer	
SelfContainedSubCatchment	Returns True if this subcatchment has no upstream input, otherwise False	True / False	
ThroughFlowSubCatchment	Returns True if this subcatchment has upstream input, otherwise False	True / False	
CatchmentOutlet	Returns True if this subcatchment's outlet is the catchment outlet, otherwise False	True / False	
NumberOfBoundaryPolygons	Number of polygons that define the subcatchment boundary	integer	
BoundaryPolygons[j].NoOfVertex	Number of vertexes associated with this boundary polygon 'j'	integer	
BoundaryPolygons[j].Vertex[k].Easting	Easting of this vertex 'k' of this boundary polygon 'j'	decimal	user coordinate
BoundaryPolygons[j].Vertex[k].Northing	Northing of this vertex 'k' of this boundary polygon 'j'	decimal	user coordinate
NumberOfPerimeterPixels	Number of pixels in this subcatchment that lie on the subcatchment perimeter	integer	
PerimeterPixel[j].Row	Row number of this perimeter pixel 'j' of this subcatchment	integer	
PerimeterPixel[j].Column	Column number of this perimeter pixel 'j' of this subcatchment	integer	
NumberOfOutletPixels	Number of pixels in this subcatchment that define the subcatchment outlet	integer	
OutletPixel[j].Row	Row number of this outlet pixel 'j' of this subcatchment	integer	
OutletPixel[j].Column	Column number of this outlet pixel 'j' of this subcatchment	integer	

Junction Variables

The following project variables relate to the *Junction* variable category. They refer to the attributes of junctions in the nodal network relationship. Junctions are indicated in CatchmentSIM by solid circles drawn at the intersection of subcatchment links in the subcatchment network. All junctions except the outlet junction have a downstream subcatchment and all junctions have at least one upstream subcatchment.



These project variables must all be prefixed with **%Junction.** eg., *%Junction.DownstreamSubCatchment*.

PROJECT VARIABLE *(%Junction.)*	DESCRIPTION	OUTPUT TYPE	UNITS
DownstreamSubCatchment	Subcatchment ID number of subcatchment downstream of this junction	integer	
NumberOfUpstreamSubCatchments	Quantity of immediate upstream subcatchments from this junction	integer	
Easting	Easting of this junction	decimal	user coordinate
Northing	Northing of this junction	decimal	user coordinate
DistanceToDownstreamJunction	Flow path distance to from this junction to downstream junction	decimal	m
AverageSlopeToDownstreamJunction	Average vectored slope along flow path from this junction to downstream junction	decimal	m/m
UpstreamSubCatchment[j]	Subcatchment ID number of immediate upstream subcatchment 'j' (ie., there may be more than one upstream subcatchment)	integer	

DEM Pixel Variables

The following project variables relate to the *DEM Pixel* variable category. They refer to statistics and values for an individual pixel of the DEM. The particular DEM pixel is identified by the integer value referenced in the square brackets following the *%DEMPixel* keyword where ***i*** is the pixel row number and ***j*** is the pixel column number.

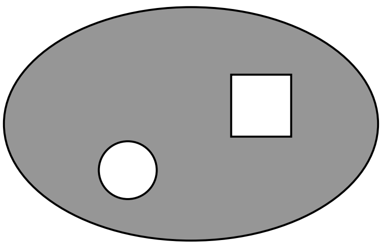
These project variables must all be prefixed with **%DEMPixel[i][j].** Where ***i*** and ***j*** are integer vales, integer type project or user variables or loop substitution letters. eg., *%DEMPixel[i][j].CentroidEasting*.

PROJECT VARIABLE *(%DEMPixel[i][j].)*	DESCRIPTION	OUTPUT TYPE	UNITS
CentroidEasting	Easting of pixel centroid	decimal	user coordinate
CentroidNorthing	Northing of pixel centroid	decimal	user coordinate
MaxEasting	Easting of most eastward side of pixel	decimal	user coordinate
MaxNorthing	Northing of most northward side of pixel	decimal	user coordinate
MinEasting	Easting of most westward side of pixel	decimal	user coordinate
MinNorthing	Northing of most southward side of pixel	decimal	user coordinate
Elevation	Pixel elevation	decimal	m
FlowDirection	Pixel flow direction	decimal	degrees
Subcatchment	Subcatchment ID number of parent subcatchment	integer	
ImperviousProportion	Impervious proportion of pixel based on impervious polygons and background impervious proportion values	decimal	m^2/m^2
NumberOfContributingPixels	Quantity of upstream pixels that flow into this pixel (Flow Accumulation)	integer	
ContributingArea	Combined area of upstream pixels that flow into this pixel	decimal	m^2
DistanceToSubCatchmentOutlet	Overland flow distance from pixel to subcatchment outlet	decimal	m

Impervious Areas

The following project variables relate to the *Impervious Areas* variable category. They refer to imported or Heads Up Digitised impervious area polygons in the CatchmentSIM project and also to options selected for the background impervious proportion and method of treatment for overlapping polygons as selected in the Impervious Areas Form.

CatchmentSIM can handle complex multi-region polygons such as island polygons. These polygons are described by multiple vertex sets called regions. For example the complex polygon shown below consists of three regions, the first describes the outer perimeter while the second and third regions describe the internal polygons (*ie., areas omitted from the complex polygon surface*). Simple polygons have only one region.



These project variables must all be prefixed with **%ImperviousAreas.**

PROJECT VARIABLE *(%ImperviousAreas.)*	DESCRIPTION	OUTPUT TYPE	UNITS
IMPPolygonsExist	Returns True if impervious area polygons exist in the current project, otherwise False	True / False	
BackgroundIMPProportion	The background impervious proportion selected in the Impervious Areas Form	decimal	m^2/m^2
OverlappingIMPPolygonsOption	Returns a description of the method of treatment selected for overlapping impervious area polygons in the Impervious Areas Form	text	
NumberOfIMPPolygons	The number of impervious area polygons in the project	integer	
IMPPolygon[i].ImperviousProportion	The impervious proportion of this impervious area polygon 'i'	decimal	m^2/m^2
IMPPolygon[i].NumberOfRegions	The number of regions in this impervious area polygon 'i'	integer	
IMPPolygon[i].Region[j].NoOfVertex	The number of vertex in this region 'j' in this impervious area polygon 'i'	integer	
IMPPolygon[i].Region[j].Vertex[k].Easting	The easting of this vertex 'k' in this region 'j' in this impervious area polygon 'i'	decimal	user coordinate
IMPPolygon[i].Region[j].Vertex[k].Northing	The northing of this vertex 'k' in this region 'j' in this impervious area polygon 'i'	decimal	user coordinate

Synthetic Streams Variables

The following project variables relate to the *Synthetic Streams* variable category. They refer to statistics and values for the vector synthetic stream network that can be calculated by CatchmentSIM.

These project variables must all be prefixed with **%SyntheticStreams.**

PROJECT VARIABLE *(%SyntheticStreams.)*	DESCRIPTION	OUTPUT TYPE	UNITS
AdoptedSATPixels	The number of pixels that was used as the Stream Area Threshold (SAT) value for generating this synthetic stream network	integer	
AdoptedSATArea	The SAT area corresponding the SAT number of pixels	decimal	m^2
MaxHortonOrder	Maximum Horton order of the synthetic stream network	integer	
NumberOfStreamSegments	The number of stream segments in the synthetic stream network	integer	
StreamSegment[i].Length	The vector length of this synthetic stream segment 'i'	decimal	m
StreamSegment[i].HortonOrder	The Horton order of this synthetic stream segment 'i'	integer	
StreamSegment[i].Subcatchment	The subcatchment ID value that this synthetic stream segment 'i' is situated within	integer	
StreamSegment[i].DownstreamSegment	The synthetic stream segment ID value for the synthetic stream segment immediately downstream of this synthetic stream segment 'i'	integer	
StreamSegment[i].NoOfVertex	The number of vertex within this synthetic stream segment 'i'	integer	
StreamSegment[i].Vertex[j].Easting	The easting of this vertex 'j' in this synthetic stream segment 'i'	decimal	user coordinate
StreamSegment[i].Vertex[j].Northing	The northing of this vertex 'j' in this synthetic stream segment 'i'	decimal	user coordinate

Contour Data Variables

The following project variables relate to the *Contour Data* variable category. They refer to the attributes of imported contour lines. These project variables must all be prefixed with **%ContourData.** eg., *%ContourData.Exists*.

PROJECT VARIABLE ***(%ContourData.)***	DESCRIPTION	OUTPUT TYPE	UNITS
Exists	Returns True if contour data exists, otherwise False	True / False	
NumberOfContours	Number of contour segments	integer	
ContourLine[i].Elevation	Elevation of this contour segment 'i'	decimal	m
ContourLine[i].NumberOfVertex	Number of vertex in this contour segment 'i'	integer	
ContourLine[i].Vertex[j].Easting	Easting of this vertex 'j' of this contour segment 'i'	decimal	user coordinate
ContourLine[i].Vertex[j].Northing	Northing of this vertex 'j' of this contour segment 'i'	decimal	user coordinate
ContourLine[i].Vertex[j].InSubCatchment[k]	Returns True if this vertex 'j' of this contour segment 'i' is within the subcatchment with ID value equal to 'k', otherwise False	True / False	
ContourLine[i].Vertex[j].WithinCatchment	Returns True if this vertex 'j' of this contour segment 'i' is within the catchment, otherwise False	True / False	

Stream Data Variables

The following project variables relate to the *Stream Data* variable category. They refer to the attributes of imported stream lines. These project variables must all be prefixed with **%StreamData.** eg., *%StreamData.Exists*.

PROJECT VARIABLE ***(%StreamData.)***	DESCRIPTION	OUTPUT TYPE	UNITS
Exists	Returns True if stream data exists, otherwise False	True / False	
NumberOfStreams	Number of stream segments	integer	
StreamLine[i].NumberOfVertex	Number of vertex in this stream segment 'i'	integer	
StreamLine[i].Vertex[j].Easting	Easting of this vertex 'j' of this stream segment 'i'	decimal	user coordinate
StreamLine[i].Vertex[j].Northing	Northing of this vertex 'j' of this stream segment 'i'	decimal	user coordinate
StreamLine[i].Vertex[j].InSubCatchment[k]	Returns True if this vertex 'j' of this stream segment 'i' is within the subcatchment with ID value equal to 'k', otherwise False	True / False	
StreamLine[i].Vertex[j].WithinCatchment	Returns True if this vertex 'j' of this stream segment 'i' is within the catchment, otherwise False	True / False	

Background Image Variables

The following project variables relate to the *BackgroundImage* variable category. They relate to the background image that may be exported using the **ExportBackgroundPicture** procedure.

These project variables must all be prefixed with **%BackgroundImage.** eg., *%BackgroundImage.MaxEasting*.

PROJECT VARIABLE ***(%BackgroundImage.)***	DESCRIPTION	OUTPUT TYPE	UNITS
MaxEasting	Easting of most eastward point of screen display at time of export	decimal	user coordinate
MaxNorthing	Northing of most northward point of screen display at time of export	decimal	user coordinate
MinEasting	Easting of most westward point of screen display at time of export	decimal	user coordinate
MinNorthing	Northing of most southward point of screen display at time of export	decimal	user coordinate

Date / Time Variables

The following project variables relate to the *Date / Time* variable category. They reveal information about the time and date the script was processed.

These project variables must all be prefixed with **%DateTime.** eg., *%DateTime.ShortTime*.

PROJECT VARIABLE ***(%DateTime.)***	DESCRIPTION	OUTPUT TYPE	UNITS
DayAsNumber	Current day as a number 1-31	text	
DayAsWord	Current day as a word eg., Monday	text	
MonthAsNumber	Current month as a number 1-12	text	
MonthAsWord	Current month as a word eg., January	text	
Year	Current year as four digit value eg., 2003	text	
ShortDate	Current date in short format (dd/mm/yyyy)	text	
Second	Current second as two digits	text	
Minute	Current minute as two digits	text	
Hour	Current hour as two digits	text	24hr clock
ShortTime	Current time in short format (hh:mm:ss)	text	24hr clock

APPENDIX C

RELEVANT PUBLICATIONS

AUTOMATION OF WBNM HYDROLOGIC MODELING USING GIS AIDED TOPOGRAPHIC PARAMETERISATION

Chris Ryan [1], *Michael Boyd* [2]
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[2] Associate Professor, University of Wollongong, NSW, Australia

Abstract

This paper describes the development of a GIS interface which can be used to construct lumped hydrologic models for flood estimation on natural and urban catchments. The interface is currently being implemented with the runoff routing model WBNM, but is a general procedure and could be used with a range of flood hydrograph and daily flow models.

The GIS interface utilises digital contour and watercourse data to automatically delineate subcatchments, to measure generalised subcatchment attributes, and to allocate lag times to the subcatchments. The key algorithms in the GIS interface are compared with traditional manual map interpretation techniques, and to some currently available GIS procedures.

The GIS interface dramatically reduces the time required to delineate subcatchments and measure their topographic and hydrologic attributes. It also has significant potential to increase the reproducibility and accuracy of streamflow prediction, while reducing the inherent user subjectivity involved in more traditional methods.

Key Words: GIS, Hydrologic Modelling, Digital Elevation Model, DEM, Runoff Routing

Introduction

Hydrologic modelling plays an important role in flood studies in Australia. Disciplines in which flood hydrographs are required range across a broad spectrum from land development applications, to environmental legislation, and floodplain management strategies.

The increasing availability of GIS data-sets is having a marked effect on the development of hydrologic modelling techniques. The information contained within these data-sets allows the application of geo-computational algorithms to determine topographic and hydrologic attributes of subcatchments at a scale not practicable by traditional methods. Furthermore, the abundance of extractable geo-statistics provided by these algorithms also reduces the guesswork involved in defining lag parameters for hydrologic models.

This paper describes development of an automated GIS interface designed to generate topographic and hydrologic attributes for use with the lumped hydrologic model WBNM.

The following sections describe the structure of the GIS interface and the algorithms that have been developed to automate the process. Particular attention is given to those algorithms that incorporate the automated decision structures that allow aggregation of waterway and contour data to produce a comprehensive digital terrain representation.

Current Industry Techniques for Hydrologic Modelling

At the present time, most flood studies use lumped hydrologic models. By their nature, these models require subdivision of the catchment into a large number of subcatchments, which are assumed to consist of relatively homogeneous topographic and hydrologic attributes (Boyd et al, 1996).

These subcatchments are arranged in a flow matrix that represents the stream network on the real catchment. Lag relations are used to allocate lag times to each subcatchment, and to the stream segments connecting the subcatchments.

Rainfall, in the form of design storm temporal patterns or recorded historical storms, are applied to the model to generate flood hydrographs at the outlet of each subcatchment and at the main catchment outlet.

Catchment Delineation

Currently, delineation of catchment boundaries from topographic maps is done by hand in most cases. Catchments and subcatchments are delineated using contour lines to determine watershed boundaries. Division of the catchment into subcatchments is achieved by locating subcatchment outlets at the confluence of major tributaries with the main stream, or at their confluence with a higher order tributary. The procedure is time consuming and to some extent subjective.

Primary Subcatchment Attributes

Lumped hydrologic models require a range of topographic and hydrologic attributes to be defined for each subcatchment. Primary attributes are those able to measured directly from readily available GIS data. These attributes may be categorised into two groups, those that have a distinct single value for each subcatchment such as area and impervious fraction, and those attributes that can vary over the subcatchment such as roughness, slope, soil and vegetation. In contrast to the assumptions in lumped hydrologic modelling, the attributes in the latter group are unlikely to be entirely homogenous over a subcatchment. Hence, assignment of an attribute to a subcatchment involves development of an average or generalised value.

Generalised attributes are often determined by a ‘best-guess’ approach, or are based on a small number of measurements made at selected points within the subcatchment. These decisions are often subjective and may be difficult to reproduce with consistency. Accurate calculation of a subcatchment attribute involves processing a large amount of data. Such calculations are usually impractical by hand, but they lend themselves well to automation using GIS based algorithms.

Secondary Subcatchment Attributes

Secondary catchment attributes are those that have a functional relationship to one or more primary attributes. Rainfall-runoff models typically require several secondary attributes to be defined. Specifically, WBNM requires definition of rainfall loss rates and lag parameters.

Rainfall losses are related to soil, vegetation, land-use, antecedent moisture conditions, and may also be related to topographic attributes. Much of this information can be obtained as spatially distributed GIS data-sets.

Lumped hydrologic models also require specification of lag parameters for each subcatchment. These parameter values are used to determine a time lag for flood routing of the hydrograph to the downstream subcatchment. WBNM uses three types of lag parameters: for routing of overland flow in natural catchments; routing runoff from impervious surfaces in urban catchments; and routing of hydrographs in streams. Each of these parameters is dependent on the topographic attributes of the subcatchments.

The dominant influence on lag times is the size of the subcatchment and, for urban catchments, the impervious fraction. Second order influences may include stream slopes, surface roughness and drainage density. GIS algorithms have the potential for rapid measurement of these attributes, allowing the investigation of relationship between them and subcatchment lag times.

Potential Contribution of GIS Integration

While subcatchment delineation, measurement of topographic and hydrologic attributes, and determination of model lag parameters is usually done by hand, all of these tasks are governed by logical rules which have the potential to be translated to computer code. GIS applications have shown some promise in their ability to reproduce catchment delineation and parameterisation techniques. However, in practice we are yet to see a large scale shift from hand calculations to GIS based techniques.

Automation of the tasks associated with setting up a hydrologic model, such as WBNM, produces considerable benefits. Significant time saving is possible and the methods present potential for a tangible increase in the accuracy and reproducibility of results, with a corresponding reduction in user subjectivity.

The GIS interface and the algorithms it employs to substitute these manual techniques are described in the following sections.

Structure of the GIS Interface

The GIS interface can be categorised into four sequential program components. These are:

1. Development of a Digital Elevation Model (DEM) by importing and conversion of vector GIS data, followed by interpolation of unassigned pixels;

2. Assessment and preprocessing of the DEM to make it compatible with hydrologic modelling;

3. Flow routing mechanisms superimposed over the DEM; and,

4. Geo-spatial statistical analysis of the DEM in order to generalise subcatchment attributes and lag parameters for use with WBNM.

Development of Digital Elevation Model

The Digital Elevation Model forms the basis of the GIS interface. It is a raster (*grid*) structure of rectangular pixels, where each pixel can be identified by a row and column number.

The DEM is developed by raster conversion of vector contour and watercourse data, and interpolation of the remaining unassigned pixels. Algorithms are employed to ensure drainage is maintained along observed watercourses, and to aid representation of ridge lines and other topographic features, which the GIS model may find difficult to interpolate directly from the source data.

Source Data

The base GIS data required by the algorithms can be imported from a number of data storage formats compatible with many commercial GIS platforms. Typical data requirements to allow development of a good terrain representation include 3D contour lines and 2D vector maps of known watercourses.

This data is imported into the application and stored in a compressed internal format for use in development of the raster DEM.

Vector to Raster Conversion

The first stage in the process of forming the DEM is to incorporate the vector contour data and assign the contour elevation value to all pixels underlying the contour line. All pixels underlying the line are assigned this elevation, with the exception of pixels that do not meet the following rule:

If a vector line being converted to a raster representation passes from the last assigned pixel and traverses two of the neighboring 8 pixels then only the pixel containing the longer line segment will be assigned.

This rule is generally recognised to be appropriate for a vector to raster conversions (Van Der Knapp, 1992) to avoid a zero-width line being converted into a two pixel width raster representation as shown in **Figure 1**.

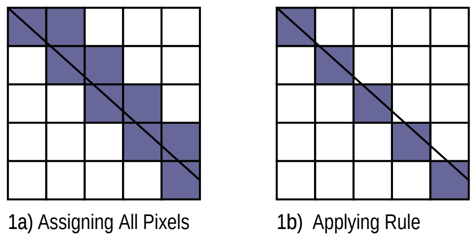

Figure 1: Vector to Raster Conversion

Incorporation of Watercourse Information

If known watercourse information has been imported then this data is also incorporated into the DEM. The algorithm interprets known watercourse flow-paths as lines where elevations should consistently and linearly decrease (*in a downstream direction*) between intersected contour lines. The flow-path elevation interpolation algorithm processes watercourse data in accordance with the following rules:

1. The main stream is selected as the known watercourse flow-path beginning at the highest elevation. Elevations of pixels underlying this flow-path are linearly interpolated between intersected contour lines until a DEM boundary is reached.

2. Each of the remaining watercourses are processed sequentially from those starting from the highest elevation to those starting from the lowest elevation. Pixel elevations along each tributary are interpolated linearly until a junction with a previously interpolated flow path is reached.

This algorithm has the capacity to resolve an unlimited number of intersections of three vector watercourse junctions (*a lateral inflow and main-stream line segments above and below its intersection*) and decision structures have been implemented in order for the algorithm to decide which segment to process next in order to continue interpolating in a downstream direction.

The outcome of the algorithm is preservation of an observed stream network in the DEM. This can be seen by the calculated flow-paths shown in **Figure 2.** The green lines (*dashed*) in this image represent the calculated flow-paths originating from targeting the flow routing algorithm on 5 selected points in the DEM. It can seen that in the areas where known watercourses have been incorporated into the model (*solid blue lines*) the calculated flow-paths will closely follow the same path in almost all cases.

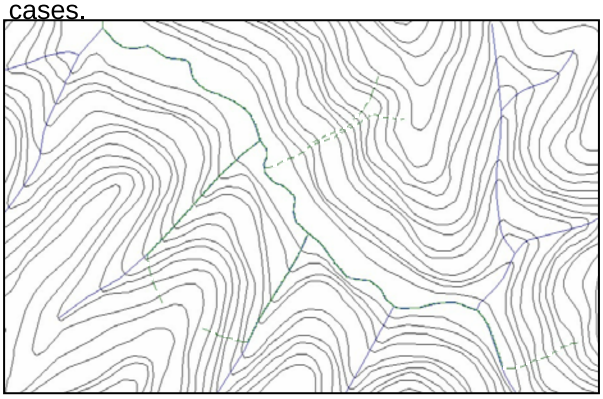

Figure 2: Incorporation of Watercourse Data

Interpolation of Unassigned Pixels

Once all imported data is incorporated into the DEM, the program interpolates elevations for all unassigned pixels (*ie., those not underlying a contour line or known watercourse*). This is achieved by implementing a ray based pixel interpolation algorithm. The level of definition of the interpolation engine is defined by the user, based on the required accuracy and available computational resources.

The methodology behind the interpolation algorithm is based on a distance weighted average of a series of linear interpolations along a set number of cross-sections taken through the pixel. For example, the interpolation regime shown in **Figure 3** exhibits a 16 ray interpolation sequence. The 180 degree arc is divided into 8 increments and interpolation rays are initiated at the appropriate angles. All rays are paired with a mirror ray which travels in the opposite direction (*ie., + 180 degrees*).

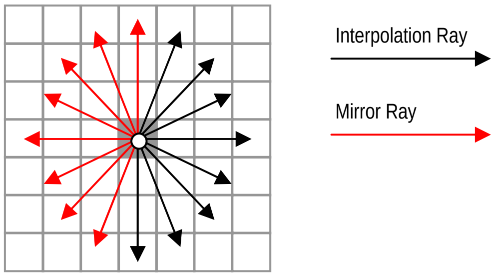

Figure 3: Ray Based Interpolation Methodology

Once an interpolation ray and its corresponding mirror ray each intersect a pixel with an assigned elevation, linear interpolation is applied to determine the approximated pixel elevation for that particular interpolation and mirror ray combination. The final value for the pixel is based on a weighted average of all the cross-section interpolations. The basis for weighting the derived elevations (*16 in the current example*) is the distance between the assigned pixels that form each end of the linear cross-sections.

The program allows the user to designate the number of interpolation rays (*and mirror rays*) that are used to interpolate the pixel elevation. This study has found that increasing the definition of the algorithm largely improves the DEM interpolation result with a relatively small cost in computational time.

This technique does have shortcomings, namely, it can have difficulty representing hill peaks and ridge lines unless additional data are incorporated. This may be seen in **Figure 4** which depicts a cross-section generated from a DEM interpolated using the ray based algorithm. The cross section alignment is shown in red and the flattened crest may be seen in the highlighted section of the corresponding cross-sectional plot.

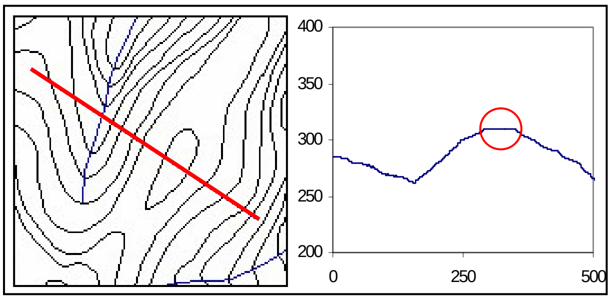

Figure 4: Anomalies in DEM Interpolation

The program allows for the implementation of additional spot heights, 'heads-up' digitising of artificial contours and placement of Interpolation Training Lines (ITL) to overcome these problems and generally improve the resulting DEM.

There is potential to incorporate other algorithms utilising more advanced mathematics to improve the DEM interpolation. Kriging and surface fitting techniques have demonstrated some capability to produce good approximations of natural surfaces (Wise, 2000). However, since these methods are not constrained by the closest contours, they are often prone to creating artificial holes and peaks which have a detrimental effect on rainfall-runoff simulation.

Furthermore, these methods can require unfeasible computation times for the interpolation algorithms whereas the ray based method adopted in this study can be applied to a DEM containing millions of pixels in a matter of minutes.

Hydrologic Preprocessing of DEM

In order for the Digital Elevation Model to be applied in a flood study it needs to be pre-processed to ensure its suitability for hydrologic modelling. In particular, flat areas and localised depressions must be treated to ensure flow from each pixel can be routed downslope until ultimately leaving the DEM boundaries.

The program currently treats flat and depression phenomena by raising pixel elevations until they are greater than their lowest neighbour. This technique would seem to be appropriate in most cases where flat areas or single pixel depressions are likely to be due to inaccuracy in DEM interpolation or lack of definition in the source data. However, scope exists for the introduction of breaching algorithms for treatment of more complex drainage anomalies.

Rainfall Runoff Routing

The flow routing algorithm embedded in the program involves a single direction 360 degree flow direction formula based on the steepest flow direction vector. Flow is considered to originate at the center of a pixel and flow downslope according to each pixel's drainage angle until the catchment outlet is reached. In this manner, the entry and exit points of flow through all downstream pixel are modelled, and an accurate representation of distance to outlet, overland drainage path length and average flow-path slope can be ascertained.

As flow is represented by a line, it is only permitted to enter one of its four immediate neighbours. Diagonal pixels may be accessed by traversing through a side pixel. Consequently, the algorithm bases its calculation on the four pixels which share a non-zero boundary length (*ie., diagonal pixels are not included*).

The flow direction angle is calculated according to the following rules and as shown in **Figure 5:**

1. The neighbouring pixel with the steepest downward slope is identified out of the four adjacent pixels. The magnitude and direction of this slope is assigned as the primary slope vector.

2. The neighbouring pixel on either side of the steepest downward slope pixel (*diagonal pixels are not included*) are tested to ascertain whether they are also downhill. If one or both of these pixels are downhill then the steepest of these is assigned as the secondary slope vector and the resultant flow angle is calculated by the hypotenuse of the primary and secondary slope vectors. Alternately, if neither of these are downhill then the flow vector is assigned immediately into the steepest slope pixel (*ie., 0, 90, 180 or 270 degrees*).

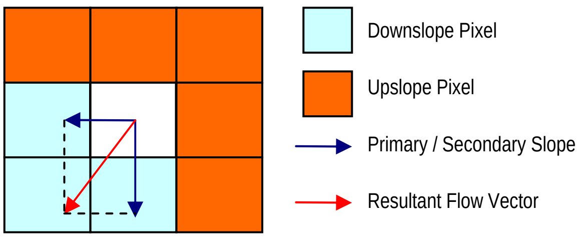

Figure 5: Flow Routing Algorithm

The capability of the flow direction angle to assume any value from 0-360 degrees as allowed in this study is a distinct advantage over the flow routing algorithms used by many GIS applications. Often these programs simply allocate flow from a pixel to one of its eight neighbours by calculation of the steepest descent path. This method, known as the D8 method, has been shown to produce poor results due to its approximation to the nearest 45 degrees (*in a square grid*) and its failure to represent convergent flow (Turcotte et al, 2001). Errors generated by the D8 method also have a tendency to propagate and increase down a hillslope. To illustrate this, downslope flow paths generated for 6 selected DEM pixels by the algorithm used in this study, and by the traditional D8 method are contrasted in **Figure 6**.

The D8 generated flow-paths are shown in brown (*dashed line*) while the results produced by the algorithm in this study are shown in green (*solid line*). It can be seen that the algorithm employed in the program produces flow-paths that are more natural and are better able to intersect contour lines (*source data*) at right angles. Moreover, the propagation of errors using the D8 method is clearly shown in the highlighted area.

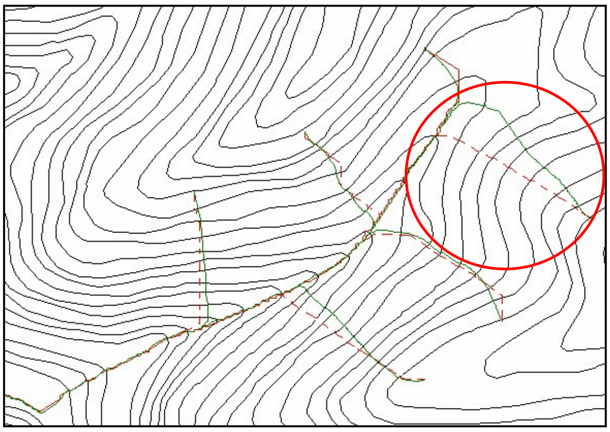

Figure 6: D8 Method vs Flow Routing Algorithm

There is still room to improve the flow direction algorithm and remove its dependency on the simplifying (*and incorrect*) assumption that flow originates from one point in each pixel and flows in a single direction (Costa-Cabral & Burges, 1994). Algorithms that can overcome these difficulties are classed as multiple direction algorithms and distribute a proportion of flow from each pixel to two or more of the neighboring downslope pixels. These algorithms are better able to represent divergent flow however, their computational efficiency and robustness are yet to be adequately demonstrated.

Generation of Stream Network

Once the flow direction angles for each pixel have been formulated it is possible to develop a stream network from the DEM. The network information is stored in a flow accumulation matrix. Each pixel is routed downslope until it exits the DEM, and the flow accumulation matrix value is indexed for each pixel that the flow-path travels through. After completion of this flow routing, the flow accumulation matrix contains the number of upslope pixels that drain through each pixel in the DEM. This enables automated delineation of the contributing subcatchment for any pixel within the DEM.

Streams are designated by a threshold area value. That is, once a pixel drains more than a specified area (*number of pixels * pixel area*) it is designated a stream pixel. The embedded animation (*refer link below*) illustrates the effect on the stream network of reducing the threshold area towards 1 – for which case all pixels will be stream pixels.

Stream Network Animation

Geo-Spatial Statistics and Definition of WBNM parameters

An important aspect in the application of lumped hydrologic models is the assignment of lag times to the subcatchments. Lag times are related to the subcatchment topographic attributes and are determined in the models from equations derived from observed hydrographs and measured subcatchment attributes. Thus both the development of lag relations using observed hydrographs, and the application of these relations to allocate lag times within the model, require extensive measurement and geo-statistical analysis of the subcatchment attributes. GIS interfaces are eminently suitable for this analysis.

Although this component of the program is yet to be finalised, it is envisaged that a relationship could be derived between the WBNM lag parameter and certain geo-statistical parameters that can be extracted using the GIS interface after analysis of all pixels within a particular subcatchment. Data analysis studies will need to be conducted to determine these relationships, however some topographic measures that have been suggested to play a role the hydrologic response of a subcatchment include:

- Average distance to subcatchment outlet for each pixel;
- Average overland flow distance for each pixel;
- Average in-stream distance for each pixel;
- Average slope;
- Drainage density and,
- Stream bifurcation ratio.

Conclusions

Simulation of rainfall runoff phenomena by lumped hydrologic models is an important component of quantitative streamflow analysis in Australia. The increasing availability of GIS data-sets gives the potential for automation of many of the tasks associated with preparing a lumped hydrologic model.

This paper has presented the beginnings of a freely available stand-alone GIS interface for the lumped hydrologic model WBNM. The algorithms used in the interface have been described. Comparisons have been made with some simpler but less effective GIS algorithms.

The GIS interface shows considerable potential to increase the accuracy of streamflow prediction by reducing the subjectivity involved in assigning catchment parameters and subcatchment lag relationships, particularly in catchments that lack historical hydrologic data.

Future Research

This research project was initiated in March 2001 and software development has only been underway for a few months, consequently, the WBNM GIS interface is still in the development phase. However, It is anticipated that by the time of the conference, the final program components will be completed and ready for application in flooding investigations.

Development of the application will continue and the focus will remain on building a robust industry tool rather than a purely research orientated application. The goals will remain: automation, reproducibility and accuracy enhancement of currently accepted techniques for rainfall-runoff analysis.

Software Availability

A free to download version of the current program with a short tutorial is available on the project web-site. Future versions of the software and relevant documentation will be added as soon as possible. Users can also register for a mailing list that is also available should you wish to be notified of updates.

The hydrologic modelling package WBNM is also available as a free download from its web-site.

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Authors Biographies

Chris Ryan is currently undertaking a postgraduate research degree in the field of simulation and modelling of rainfall-runoff phenomena. His research direction has evolved from his honours degree in Environmental Engineering and experience in the consulting industry. His current project specialises in Windows programming at the interface of GIS data platforms and non-linear hydrological modelling. He is undertaking his work at the University of Wollongong in association with Michael Boyd, co-creator of WBNM. He also works for the Sydney based consulting firm Patterson Britton & Partners.

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AUTOMATED CATCHMENT PARAMETERISATION FOR RUNOFF ROUTING MODELS UTILISING 3D GIS CONTOUR INFORMATION

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Abstract This paper describes the development of a comprehensive subcatchment parameterisation tool and GIS interface for hydrologic modelling. The interface has been tailored to automate the currently predominantly manual process of setting up lumped hydrologic models for flood estimation on natural and urban catchments.

Key outcomes of the research are rapid, reproducible and accurate automated delineation of subcatchments, measurement of generalised topographic attributes and determination of lag parameters. The interface also provides numerous hydrologic and topographical assessment tools to allow users to quickly determine geophysical properties of the subcatchments.

Keywords GIS, Hydrologic Modelling, Digital Elevation Model, DEM, Rainfall Runoff

Introduction

The escalating availability of GIS data-sets is having a significant effect on the development of hydrologic modelling techniques. These databases allow the application of geo-computational algorithms to determine topographic and hydrologic attributes of subcatchments at a scale not practicable by traditional methods. Furthermore, the abundance of extractable geo-statistics provided by these algorithms also reduces the guesswork involved in defining attributes that are not directly measurable from topographic data, such as lag parameters.

This paper describes a GIS based interface for lumped hydrologic models. In its current iteration, the model is tailored for full coupling with the Australian runoff routing model WBNM (Boyd et al. 1996). However, the procedures are compatible with a wide range of hydrologic, hydraulic and water balance models.

Potential Contribution of GIS to Hydrologic Modelling

Most lumped hydrologic models are currently set up using manual delineation of subcatchment boundaries and calculation of contributing areas. Generalised topographic attributes are usually determined by a 'best guess' approach or using a limited number of measurements, which are designed to be representative of the subcatchment.

GIS algorithms have the potential to dramatically increase the speed, accuracy and reproducibility of subcatchment parameterisation, with a corresponding reduction in user subjectivity. However, these GIS based approaches have not been widely adopted for use in hydrologic investigations. Three main reasons have been suggested for this trend:

(1) Lack of 3D GIS source data;
(2) Poor compatibility between GIS platforms and established hydrologic models; and,
(3) Fragile, non-flexible and oversimplified GIS algorithms.

This project aims to overcome the latter two of these issues by development of a robust and hydrologically sound set of algorithms that are fully integrated into a user-friendly GIS interface. The program allows full coupling and data exchange with lumped hydrologic models, presently WBNM. In the following sections, the methodologies behind some of the algorithms are described and compared to techniques in commonly available GIS packages. Hyperlinks to additional web-based information have been included where space restrictions have precluded full descriptions of program components.

Program Structure

The GIS interface can be categorised into four sequential program components, specifically:
(1) Development of a Digital Elevation Model (DEM) by importing and conversion of vector GIS data, followed by interpolation of unassigned pixels;
(2) Assessment and pre-processing of the DEM to ensure compatibility with hydrologic modelling;
(3) Flow routing mechanisms superimposed over the DEM; and,
(4) Geo-statistical analysis of the DEM in order to generalise subcatchment attributes and lag parameters for use with WBNM.

Development of Digital Elevation Model

The Digital Elevation Model forms the basis of the GIS interface. It is a raster (*grid*) structure of square or rectangular pixels, where each pixel can be identified by a row and column number.

The DEM is developed by raster conversion of vector contour and watercourse data, and interpolation of the remaining unassigned pixels. Algorithms are employed to ensure drainage is maintained along observed watercourses, and to aid representation of ridge lines and other topographic features, which the interpolation algorithms may find difficult to interpret directly from the source data.

The source GIS data required by the algorithms can be imported from a number of data storage formats compatible with many commercial GIS databases. Typical data requirements to allow development of a hydrologically sound terrain representation need only be 3D vector contour lines and 2D vector maps of known watercourses (*the latter being optional*). This data is imported into the application and stored in a compressed internal format for use in development of the raster DEM.

The vector source data is converted to a raster representation by selective elevation assignment of some of the pixels underlying a contour line, in accordance with accepted vector to raster conversion methodology (Van Der Knapp, 1992).

Incorporation of Watercourse Information

Imported vector watercourse data (*optional*) is interpreted by the program as pixel-paths where elevations should consistently and linearly decrease between intersected contour lines. By utilising a junction resolution and watercourse sequencing algorithm, the stream network is interpolated into the DEM. Due priority is given to higher order watercourses, which form the local minima that will shape the interpolation of the remaining DEM.

The outcome of the algorithm is preservation of an observed stream network in the DEM. This can be seen by the calculated flow-paths shown in **Figure 1**. The green (*dashed*) lines in this image represent the calculated flow-paths originating from targeting the flow routing algorithm on 5 selected points in the DEM. It can seen that in the areas where known watercourses have been incorporated into the model (*solid blue lines*) the calculated flow-paths will follow observed watercourse in almost all cases. However, occasionally in areas of very low relief, flow-paths may deviate from observed watercourses. A stream burning algorithm (*lowering all watercourse pixels by a set elevation*) is available to force the drainage patterns in these areas.

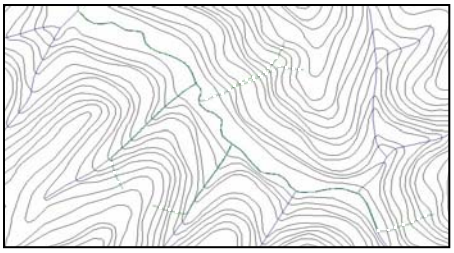

Figure 1: Incorporation of Watercourse Data

Interpolation of Unassigned Pixels

Once all imported data is incorporated into the DEM, the program interpolates elevations for all unassigned pixels (*ie., those not underlying a contour line or known watercourse*). This is achieved by implementing a ray based interpolation algorithm. The interpolation is based on a distance weighted average of a series of linear interpolations along a set number of cross-sections taken through the pixel. For example, the interpolation regime shown in **Figure 2** exhibits a 16 ray interpolation sequence. The 180 degree arc is divided into 8 increments and interpolation rays are initiated at the appropriate angles. All rays are paired with a mirror ray which travels in the opposite direction (ie., + 180 degrees).

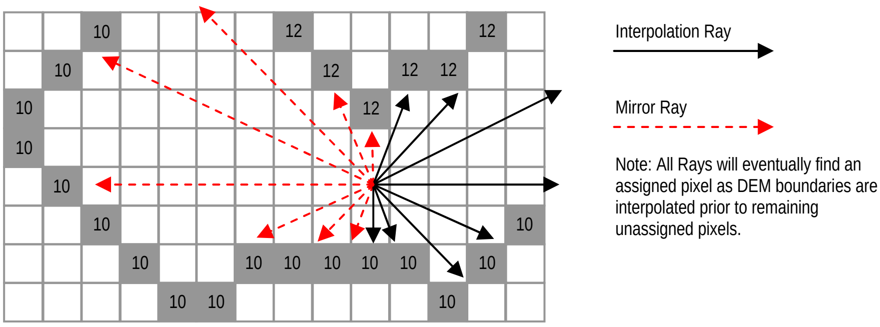

Figure 2: Ray Based Interpolation Methodology

Once an interpolation ray and its corresponding mirror ray intersect a pixel with an assigned elevation, linear interpolation is applied to determine the approximated pixel elevation for that particular interpolation ray. The final value for the pixel is based on a weighted average of all the cross-section interpolations. The basis for weighting the derived elevations (*16 in the current example*) is the distance between the assigned pixels that form each end of the ray-mirror ray cross-sections.

In order to tailor the DEM interpolation to the user's computational resources and accuracy requirements, the program allows the user to set the number of rays to use in the interpolation. Furthermore, the user may implement interpolation aids that include additional spot heights, 'heads-up' digitising of artificial contours and placement of Interpolation Training Lines (ITL). DEMs may also be imported from other interpolation programs (*such as Surfer 7*) where more advanced interpolation algorithms such as Kriging and surface fitting techniques may be applied.

These procedure have not yet be written into the program since although these techniques have demonstrated some capability to produce good approximations of natural surfaces (Wise, 2000), DEMs produced by these methods can contain undesirable sinks due to local minima of the interpolation surface equations. Furthermore, they could be seen as 'overkill' due to likely accuracy limitations of the source data (*contours*) and the long computation times required for interpolation of large DEMs with some of these methods. For comparison, the ray based method adopted in this program can interpolate millions of pixels in under 5 minutes.

Hydrologic Processing of DEM

In order for the Digital Elevation Model to be applied in a flood study it needs to be pre-processed to ensure its suitability for hydrologic modelling. In particular, flows from all pixels within the catchment must be able to be routed downslope until reaching the catchment outlet hence, any flat areas and localised depressions need to be resolved.

The most common flat areas result at hill-crests where the interpolation algorithm will flatten the hill at the final contour since the hill-crest is fully surrounded by a single contour loop (*ie., all interpolation rays will find the same contour value*). To resolve these areas the flat and depression pixels are treated by an iterative pixel filling algorithm where depression pixels are raised to the elevation of their lowest neighbour, followed by raising of all flat pixels that have a non-flat neighbour, by a small set increment, until no flat or depression pixels remain. In this manner, flattened hill-crests will be treated from the outside-inward, developing a rounded crest that will realistically distribute pixel flow-paths down all sides of the hill.

Rainfall Runoff Routing

Routing flow from each pixel downslope to the catchment outlet in a realistic manner is the most important function of the model. The downslope flow angle algorithm utilises an adapted form of the 'rolling ball' flow-path methodology first proposed by Lea (1992) to determine a flow angle for each pixel (*0-360 degrees*). Flow-paths are represented by lines and as such are only permitted to enter one of their four immediate neighbours. Diagonal pixels may be accessed by traversing through a side pixel. Consequently, the downslope flow angle algorithm bases its calculation on the four pixels which share a non-zero boundary length (*ie., diagonals pixels are not included*).

The flow direction angle for each pixel is determined from the resultant flow angle vector derived from the steepest descent non-diagonal neighbouring pixel and the steepest of its adjacent non-diagonal pixels (*if any*), as shown in **Figure 3 a**. Pixel flow-paths are mapped downslope according to each pixel's drainage angle until the catchment outlet is reached (*refer* **Figure 3 b**). In this manner, the entry and exit points of flow through all downstream pixels are modelled. For example, in the lower right pixel of **Figure 3 b** it can be seen that flow-paths from upstream pixels are distributed between both of this pixel's downslope pixels, based on where the flow-paths entered the pixel. This allows for more accurate representation of flow distribution, and calculated drainage-path length / slope statistics.

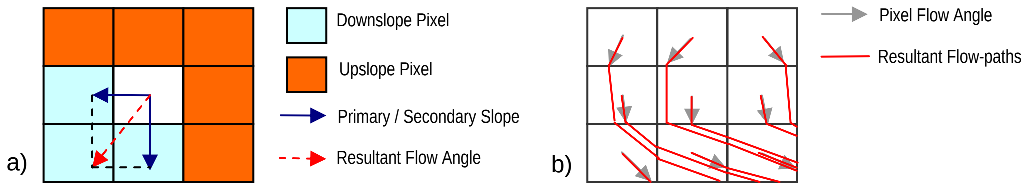

Figure 3a & b: Flow Routing Algorithm

Flow routing algorithms that map downslope flow-paths are better able to represent flow distribution in raster grids than other single direction GIS flow-routing algorithms (Costa-Cabral and Burges 1994), the most common of these being the D8 method. The D8 method simply allocates flow from a pixel to one of its eight neighbours based on which pixel represents the steepest descent. It has been shown to produce poor results due to its approximation to a cardinal or diagonal direction (Fairfield and Leymarie 1991) and its failure to represent convergent flow. The discrepancy between the D8 method (*dashed brown lines*) and the described algorithm (*solid green lines*) is shown with respect to calculated flow-paths in **Figure 4 a** and subcatchment delineation in **Figure 4 b**. These figures illustrate the tendency of the D8 method to 'snap' to cardinal or diagonal angles and the potential for these errors to accumulate in a downslope direction.

Figures 4a & 6b: D8 Method vs Described Flow Routing Algorithm

Generation of Stream Network

During the flow-path mapping, a flow accumulation value for each pixel is assigned and indexed by 1 for each flow-path that passes through the pixel. After processing of the entire DEM, the flow accumulation matrix contains the number of upslope pixels that drain through each pixel in the DEM (*ie., contributing area for each pixel*). To automatically generate a stream network, a pixel is defined as a watercourse pixel once its flow accumulation value is greater than a specified value (*Stream Area Threshold*). The embedded animation (*AVI file*) is an output tool of the GIS interface and illustrates the effect of reducing the stream area threshold towards 1 pixel (*where all pixels will be defined as watercourse pixels*), on the stream network image. This can be used as a qualitative tool to assess the differing fractal natures of subcatchments within a lumped hydrologic model.

Geo-Spatial Statistics and Definition of WBNM parameters

In addition to subcatchment topographic parameterisation, lumped hydrologic models such as WBNM require lag relations to be defined. The GIS interface can be used to establish these relations by performing geo-computational analyses on the DEM and flow-routing result database. Measures that can be quickly calculated to derive these relationships include:

Extraction of subcatchment parameters such as average vectored slope, impervious proportion, subcatchment area, drainage density, shape coefficient, mainstream slope/length and fractal statistics.

Development of subcatchment distribution charts including average 'out of stream' flow length distribution and subcatchment drainage density vs stream area threshold.

Horton characteristics (Horton 1945) such as drainage density (*Horton*), stream frequency, charting of bifurcation ratio vs stream order and best fit bifurcation ratio.

The GIS interface allows easy comparison of these geo-statistical measures and distribution charts across the subcatchment network, assisting in assigning lag parameters to the model. This is of particular importance for flood investigations where calibration using recorded rainfall and streamflow data is not possible.

Conclusions

The increasing availability of GIS data-sets gives the potential for automation of many of the tasks associated with preparing a lumped hydrologic model.

This paper has described a stand-alone GIS interface for subcatchment parameterisation that is presently fully coupled with the runoff routing model WBNM, yet could be utilised in other hydrology based applications. The algorithms in the interface have been described and comparisons have been made with some simpler but less effective GIS algorithms.

The GIS interface shows considerable potential to increase the accuracy of streamflow prediction by reducing the subjectivity involved in subcatchment parameterisation and lag relationships, particularly in catchments that lack historical hydrologic data.

The GIS interface is freely available with supporting documentation, sample data-sets and tutorials from the project web-site. The hydrologic modelling package WBNM is also available as a free download from its web-site.

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CATCHMENTSIM: A NEW GIS TOOL FOR TOPOGRAPHIC GEO-COMPUTATION AND HYDROLOGIC MODELLING

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Abstract: This paper outlines the capabilities of, and describes the algorithms employed within a freely available GIS software package specifically tailored toward hydrologic applications. The algorithms employed within CatchmentSIM are designed to overcome many of the problems associated with the simplified hydrologic algorithms adopted by conventional GIS packages. CatchmentSIM is based on a raster Digital Elevation Model (DEM) which may be interpolated internally from vector contour and stream alignment data, or imported from external applications. A Priority First Search (PFS) breaching algorithm is utilised to remove flats and pits throughout the entire DEM, which avoids the parallel stream problems that plague flat and pit removal in more common techniques. Following this, subcatchments and watercourses may be accurately delineated using a vector flow routing algorithm that has been shown to be superior to the D8 method employed by most conventional GIS applications. The CatchmentSIM software also includes a range of tools that enable topographic analysis on a scale not practicable by hand and conventional map interpretation techniques. In particular, Strahler / Horton geomorphologic analysis has been incorporated, allowing subcatchment bifurcation and drainage density relationships to be accurately determined. These techniques have been demonstrated to be more resistant to grid scale and rotation effects than comparable raster approaches in conventional GIS software packages. Following analysis of a catchment with the software, an internal macro language may be applied to export project parameters to any existing hydrologic modelling software (of a known data format) a user may wish to apply. The adopted algorithms within CatchmentSIM, enable users to build on the increasingly comprehensive information available in today's GIS, while avoiding the traditional pitfalls of conventional raster GIS techniques and maintaining tight coupling with existing 'industry standard' modelling approaches.

Keywords: CatchmentSIM, GIS, Hydrologic Modelling, Digital Elevation Model, DEM, Runoff

1. INTRODUCTION

Hydrologic modelling has an important role in flood and drainage investigations throughout the world. These models are becoming more complex and spatially variable due to their interaction with Geographic Information System (GIS).

The growing availability of large GIS data-sets and relatively powerful low-cost computing systems is allowing the development of detailed topographic analysis software that can determine topographic and hydrologic attributes of subcatchments at a scale not practicable by manual map interpretation methods.

However, It has been observed that the influence of the increasing availability of GIS terrain data sets can be slow to propagate through towards a greater conceptual or quantitative understanding of flood behaviour. The main reasons for this are thought to be:

- Poor compatibility between commercial GIS software and 'industry standard' hydrologic flood modelling computer modelling packages;
- Oversimplified and error-prone geo-spatial algorithms within conventional GIS software for calculation of terrain attributes;
- Disparity between the largely internationally standard GIS techniques, and the highly country-specific approaches to computer flood modelling; and,
- The expense associated with many conventional GIS packages / add-on modules.

Efforts to overcome these fundamental problems have resulted in the development of a standalone GIS software package specifically tailored towards hydrologic modelling, called CatchmentSIM. This free software incorporates algorithms that are more hydrologically realistic than approaches adopted by common commercial GIS packages and provides tight coupling with a range of common hydrologic modelling software packages. Thus the project allows seamless integration of the latest GIS data-sets all the way through to distributed hydrologic modelling with currently available and *'accepted'* modelling techniques.

The following sections describe the algorithms that have been developed within CatchmentSIM to provide the software's functionality and accuracy improvements over traditional commercial GIS based techniques.

2. OVERVIEW OF THE SOFTWARE

CatchmentSIM provides a user-friendly windows interface that provides access to a comprehensive range of algorithms specifically tailored towards GIS aided hydrologic investigation. Raw GIS data can be imported in most common formats and is stored in a compressed internal format. A raster Digital Elevation Model (DEM) can then be interpolated from this data or imported from an external application. Hydrologic pre-processing is applied to remove flat or pits and allow flow routing to be undertaken throughout the catchment.

The main catchment boundary may then be delineated by identification of the catchment outlet. Subcatchments may be delineated by manual designation of their respective outlets or automated break-up of the catchment into subcatchment using one of two internal algorithms. The nodal subcatchment network arrangement, hydrologic stream networks and topographic parameters are automatically calculated. CatchmentSIM also incorporates algorithms to accommodate modelling of urban structures and maintains a database of impervious areas that can be developed internally or imported from external applications. Furthermore, channels, gutters and pipes can be simulated as additional hydraulic controls that over-ride natural flow routing on the DEM. Finally, once sufficient analysis has been undertaken and subcatchment delineation and parameterisation is complete, a macro language provides tight coupling with a range of 3rd party hydrologic models and will automatically develop run-files for a chosen model (*such as WBNM, RAFTS, RORB, URBS or DRAINS in Australia*).

A more detailed description and analysis of the aforementioned algorithms is provided in the following sections.

3. INTERPOLATION OF DIGITAL ELEVATION MODEL (DEM)

As outlined previously, if an existing DEM is not available for a particular catchment, a user may wish to utilise CatchmentSIM's algorithms for interpolation of the DEM from contour and watercourse alignment data. In many cases, the interpolation of DEMs from contours and watercourse data may be preferred for hydrologic applications over other types of DEMs due to several reasons. Firstly, they can be interpolated at any scale appropriate for the catchment under analysis. Secondly, digital contour and watercourse data are widely available in many countries. Finally, contours have often been manually adjusted to better reflect the hydrologic characteristics of the natural surface and hence, are often said to contain more information than simply a string of points of common elevation (Wise, 2000). The interpolation and drainage enforcement algorithms are designed to take advantage of this extra information.

Internally interpolated DEMs are developed by raster conversion of vector contour and watercourse data, and interpolation of the remaining unassigned pixels. Algorithms are employed to ensure drainage is maintained along observed watercourses, and to aid representation of ridge lines and other topographic features.

3.1 Rasterisation of Contour Data

Imported 3D contour data is incorporated into the model by applying the contour elevation to pixels that underlie the contour alignment in accordance with accepted vector to raster conversion methodology outlined by Van Der Knapp in 1992.

3.2 Incorporation of Watercourse Information

If watercourse alignment data is available then this information is also incorporated into the DEM. The algorithm interprets known watercourse flow-paths as lines where elevations should consistently and linearly decrease (*in a downstream direction*) between intersected contour lines. The network of connected watercourse segments is analysed to determine entire streams that are mapped from their uppermost tributaries to their outlet points. Elevations are then applied to pixels underlying these watercourse segments by linear interpolation between intersected contour lines.

The outcome of the drainage enforcement algorithm is preservation of an observed stream network in the DEM. This can be seen by the calculated flow-paths shown in Figure 1. The green lines (*dashed*) in this image represent the calculated flow-paths originating from targeting the flow routing algorithm on 5 selected points in the DEM. It can seen that in the areas where known watercourses have been incorporated into the model (*solid blue lines*) the calculated flow-paths will closely follow the same path in almost all cases.

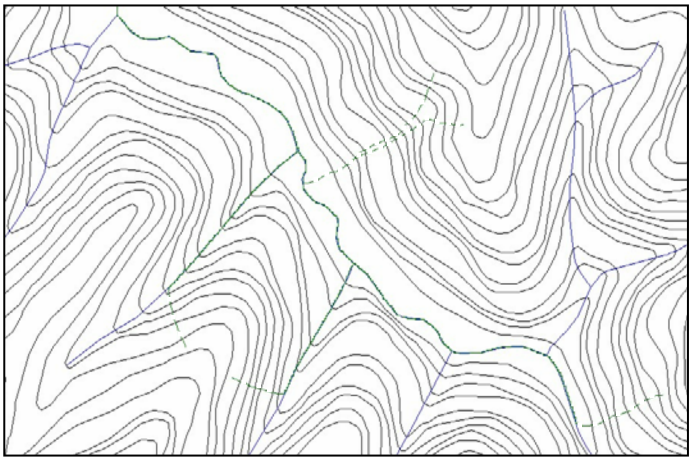

Figure 1: Incorporation of Watercourse Data

3.3 Interpolation of Unassigned Pixels

Following rasterisation of contour data and applications of the drainage enforcement algorithm, CatchmentSIM interpolates elevations for all unassigned DEM pixels. This is achieved by implementing a ray based interpolation algorithm. The level of definition of the interpolation engine is defined by the user, based on the required accuracy and available computational resources. The interpolation algorithm is based on a distance weighted average of a series of linear interpolations along a set number of cross-sections taken through the pixel.

Some interpolation anomalies may occur in regions of low contour definition. However, internal algorithms allows for the implementation of additional spot heights, 'heads-up' digitising of artificial contours and placement of Interpolation Training Lines (ITL) to overcome these problems and generally improve the resulting DEM.

4. HYDROLOGIC PRE-PROCESSING OF DEM

In order for flow routing to be able to be applied to the DEM it needs to be pre-processed to ensure its suitability for hydrologic modelling. In particular, flat areas and localised depressions must be treated to ensure flow from each pixel can be routed downslope until ultimately leaving the DEM boundaries.

Two algorithms are provided for treatment of flat and pit pixels within the DEM. A filling algorithm can be utilised which simply raises pit pixels to the elevation of their nearest neighbour, and then fills all flat pixels by a set increment to allow flow processing. This algorithm is good at treating isolated flat and pit pixels and treating some types of interpolation anomalies that can result from the aforementioned interpolation method (*such as flattened hill crests*). However, a more advanced flat and pit pixel removal method has been incorporated to treat more stubborn arrangements of flat and pit pixels.

4.1 Priority First Search (PFS) Pit Removal

The Priority First Search (PFS) algorithm is an advanced breaching algorithm that can find an outlet for any flat or pit pixel within the DEM provided a pixel with a lower elevation exists at some point within the DEM. The PFS algorithm locates an outlet pixel for each flat or pit pixel and a corresponding drainage path of least resistance between the two points. PFS algorithms are based on well documented weighted-graph theory (Sedgewick, 1988) and determine the optimum drainage path based on a priority function. The CatchmentSIM PFS algorithm has a priority function that forces an optimum drainage path for a flat or pit pixel to go through the path of lowest elevation available. If more than one potential path satisfy this criteria then the path with the largest elevation drop between the original flat or pit pixel and the identified outlet pixel is selected. If these criteria are also equal then the path with the shortest flow distance is selected. Once an optimal drainage path from a flat or pit pixel to its outlet has been found then pixel elevations along that path are lowered by linear interpolation to accommodate the drainage path.

The PFS based approach has been shown to have a number of advantages over more common drainage enforcement algorithms (Jones, 2002). The most common of these is the Jenson and Domingue algorithms (J&D

algorithms) introduced in 1989. This algorithm has been adopted in the popular ArcInfo Grid system. The J&D algorithm first fills pits to the elevation of their lowest neighbour and then assigns flow directions at flat pixels towards any neighbouring pixel that has an assigned flow direction (*that is, a non-flat pixel or a previously J&D processed flat pixel*). The major problem with this approach is that it produces areas of parallel flow paths in areas of large flat areas. The PFS approach avoids this problem as once flow paths have defined and pixel elevations along this path have been lowered, then PFS calculated optimal paths from neighbouring pixels will be attracted to this new channel, and the resulting drainage network in large flat areas will be of a fractal nature which is more representative of natural channel systems.

5. FLOW ROUTING

The flow routing algorithm adopted by CatchmentSIM determines a flow direction for each DEM pixel based on the steepest flow direction vector. Flow is considered to originate at the centre of each pixel and flow downslope according to each pixel's drainage angle until the catchment outlet is reached. In this manner, flow is modelled as a vector quantity and the entry and exit points of the flow vector through all downstream pixel are modelled, and an accurate representation of distance to outlet, overland drainage path length and average flow-path slope can be ascertained.

The flow direction angle for each DEM pixel is based on construction of a steepest descent flow vector composed from the two lowest elevation adjacent non-diagonal neighbouring pixels as illustrated in Figure 2.

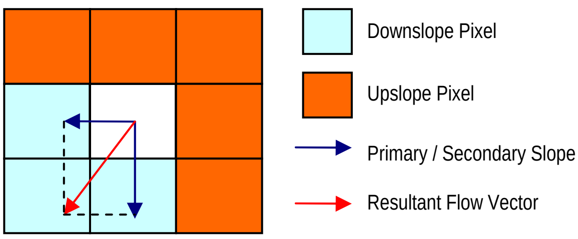

Figure 2: Flow Routing Algorithm

The capability of the flow direction angles in CatchmentSIM to assume any value from 0-360 degrees is a distinct advantage over the flow routing algorithms used by many GIS applications. Often these programs simply allocate flow from a pixel to one of its eight neighbours by approximation to the steepest descent path. This method, known as the D8 method, has been shown to produce poor results due to its approximation to the nearest 45 degrees (*in a square grid*) and its failure to represent convergent flow (Turcotte et al, 2001). Errors generated by the D8 method also have a tendency to propagate and increase down a hillslope. To illustrate this, downslope flow paths generated for 6 selected DEM pixels by the algorithm used in this study, and by the traditional D8 method are contrasted in Figure 3.

The D8 generated flow-paths are shown in brown (*dashed line*) while the results produced by the algorithm in this study are shown in green (*solid line*). It can be seen that the algorithm employed in the program produces flow-paths that are more natural and are better able to intersect contour lines (*source data*) at right angles. Moreover, the propagation of errors using the D8 method is clearly shown in the highlighted area.

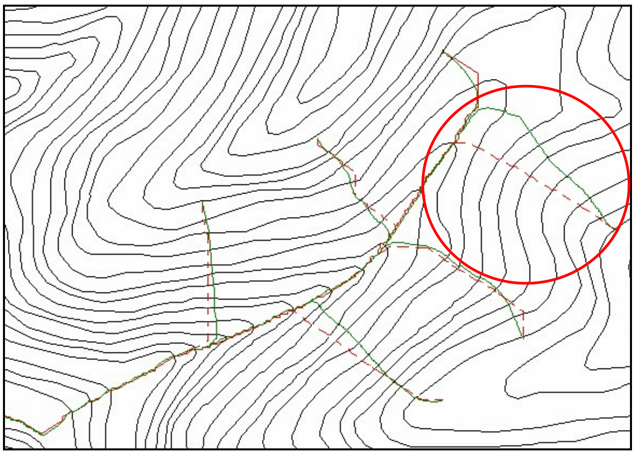

Figure 3: Comparison of D8 Method and CatchmentSIM Flow Routing

5.1 Flow Routing In Urban Areas

Urban structures have a strong influence on flow paths in urban environments but are rarely represented in DEMs or contour and watercourse data. Consequently, these structures need to be either hard-coded into the DEM or simulated as over-riding flow controls. CatchmentSIM provides tools for both of these approaches.

An example of hard-coding urban structures into a DEM is artificially raising DEM elevations along GIS layers that represent road crown alignments. Following this, the PFS algorithm can be employed to remove any resultant flat or pit pixels. This will cause the imported urban structures to be breached at their low points which results in a hydrologically realistic combination of a natural surface DEM and representation of road alignments. The resulting stream network generated by such a technique is shown in Figure 4, where the black straight lines are road crown alignments and their effect on the generated stream network is clearly illustrated.

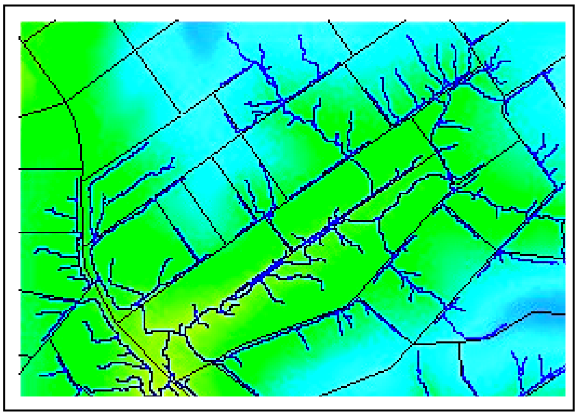

Figure 4: Effect of Roads on Stream Network

However, it is often preferable to simulate urban structures as supplementary flow controls that can be switched on or off for analysis of hydrologic events of different magnitudes, without effecting the underlying DEM. CatchmentSIM allows gutter, channels, and pipe and pit networks to be imported as hydraulic control layers. An example of a gutter hydraulic structure is shown in Figure 5.

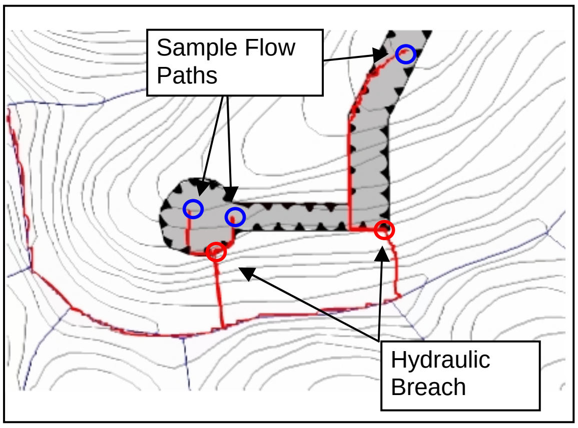

Figure 5: Effect of Gutters on Flow Paths

Calculated flow paths will follow the DEM until they intersect with a hydraulic control. In the above example of a gutter three sample flow paths have been generated. Flow will follow the gutter in whichever direction represents the steepest downslope direction. If there is no available downslope direction that follows the gutter then the algorithm will search within a distance or elevation tolerance for a pixel along the gutter with a lower elevation. This phenomenon accounts for ponding behind a gutter which effectively fills a pixel elevation and may provide a potential downslope flow path. However, if a downslope pixel along the gutter is not found within the specified tolerance then the algorithm allows for the hydraulic structure to be breached as indicated in Figure 5.

5.2 Impervious Areas Database

Many hydrologic and hydraulic models require accurate representation of impervious area proportions for each subcatchment. CatchmentSIM accommodates this requirement by maintaining a GIS database of impervious areas and allowing simple manipulation of these parameters as shown in Figure 6.

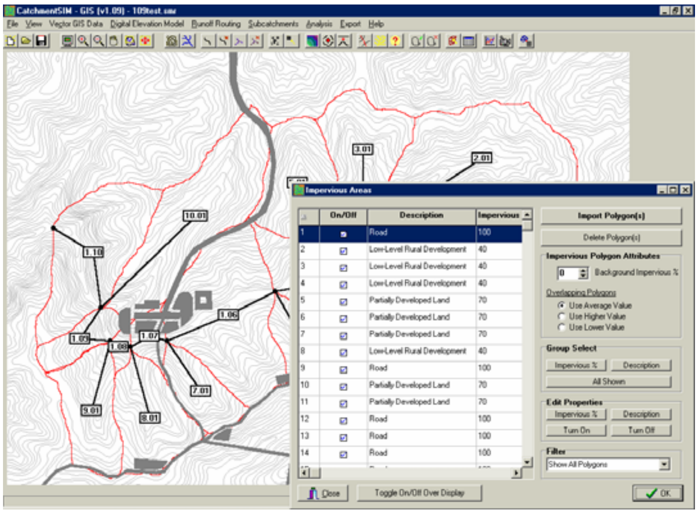

Figure 6: Impervious Areas Database

The algorithm applied to rasterise impervious polygons is able to handle complex polygons such as concave and convex polygons as well as multi-region or island polygons (*as shown in Figure 7*). DEM Pixels are determined to be within or outside of individual impervious polygons by defining a one-direction horizontal line originating from the pixel centroid and calculating the number of intersections with the polygon boundaries. Pixels with an odd number of intersections are determined to be within the polygon whereas an even number of intersections indicates a pixel outside of the polygon boundary or within an island region.

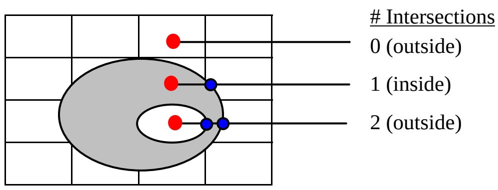

Figure 7: Algorithm for Rasterisation of Impervious Area Polygons

5.3 Generation of Stream Network

Generation of stream networks is an important component of flow routing and hydrologic analysis. CatchmentSIM allows development of both raster and vector stream networks. Following calculation of the flow direction angles for each pixel, it is possible to develop a stream network from the DEM. Each pixel is routed downslope until it exits the DEM, and the flow accumulation matrix value is indexed for each pixel that the flow-path travels through. After completion of this flow routing, the flow accumulation matrix contains the number of upslope pixels that drain through each pixel in the DEM. This enables automated delineation of the contributing subcatchment for any pixel within the DEM.

The raster stream network is simply defined by pixels whose flow accumulation value exceeds a designated Stream Area Threshold (SAT). That is, once a pixel drains more than a specified area (*number of pixels * pixel area*) it is designated a stream pixel.

5.4 Horton Stream Ordering

CatchmentSIM also includes a more complex and hydrologically realistic algorithm for representation of a vector calculated stream network. Vector representations of stream networks are preferred to raster types because they are more scale independent and enable calculation of meaningful parameters such as drainage density and shape which are based on stream lengths which are themselves vector quantities. In addition to lengths, the vector algorithm also calculates stream order values in accordance with Strahler's 1957 revision of Horton's original work (Horton, 1945) on quantitative geomorphology and stream network fractal scale-similarity. That is, the CatchmentSIM algorithm derives a set of connected polylines with calculated length values and Horton / Strahler order characteristics, enabling calculation of bifurcation and channel maintenance parameters. This is illustrated in Figure 8 where a vector stream network has been calculated for a catchment (*higher order streams have a darker line colour*) and a resulting bifurcation chart has been generated below.

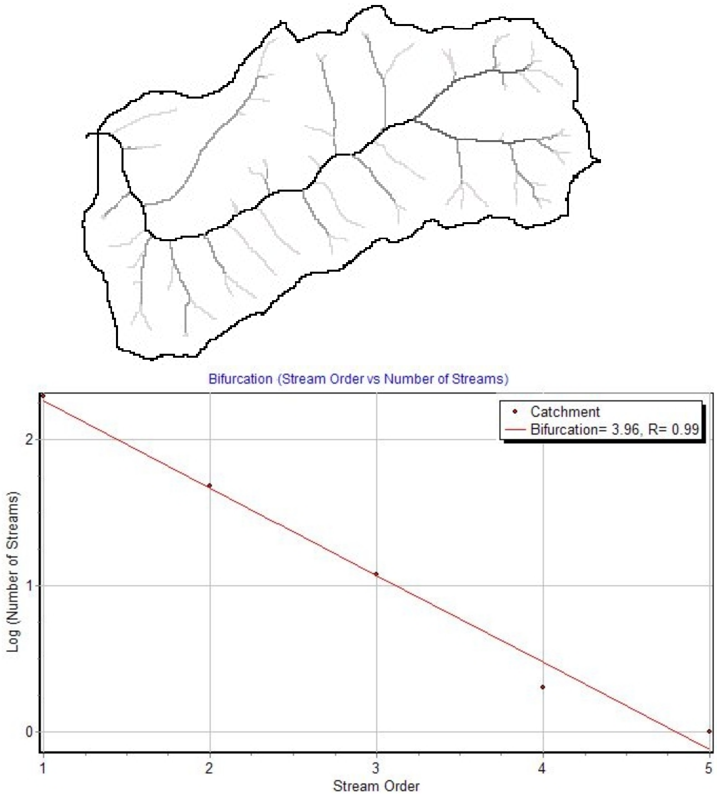

Figure 8: Vector Stream Network / Bifurcation

Interestingly, research on a number of catchments with vector stream networks derived with a different SAT values have been found to have bifurcation ratios that are scale independent and seem to concentrate around values of 4-5. This is very similar to results found by Strahler (1952 & 1957) whose work was based on manual calculation of stream lengths illustrated on maps. These similarities add weight to the argument that automated vector stream generation based on flow routing over a DEM can closely represent the fractal nature of natural stream networks, provided hydrologically accurate methods of DEM interpolation and pre-processing are applied.

Although bifurcation and stream length frequency distribution analysis have been found to be relatively constant over different catchments in various countries and climates, slight variations may be seen over subcatchments within a single CatchmentSIM project. Further research will be necessary to investigate this issue but these variations could provide evidence for differences in subcatchment rainfall response and consequently, they could provide the basis for determination of the less physically based parameters required by common hydrological modelling packages, such as subcatchment lag and routing parameters.

6. SUBCATCHMENT BREAK-UP

An important component in the development of a lumped hydrologic model is the identification of subcatchments. However, deciding how many subcatchments to use in a lumped hydrologic model and where they should be located can be a subjective decision. Two algorithms have been incorporated into CatchmentSIM to help engineers and scientists with these decisions. The first of these algorithms automatically breaks a catchment into a set number of subcatchments (*designated by the user*) based on locating subcatchment outlets at the largest jumps in the flow accumulation matrix, which represents the confluence of significant tributaries.

This algorithm can reduce the uncertainty in locating subcatchment outlets. However, the user still needs to decide on a target number of subcatchments. The number of subcatchments chosen can have a significant effect on generated hydrographs. The availability of Horton ordering allows a more quantitative basis for catchment break-up by identifying all subcatchments as a result of intersection of stream of various Horton order values. Hence, by adoption of a realistic SAT value for the particular catchment based on soil type and climate factors, the catchment break-up may be based on the more objective criteria of the stream network fractal relationship. This is shown in Figure 9 where basins of 2nd and 3rd orders have been automatically delineated.

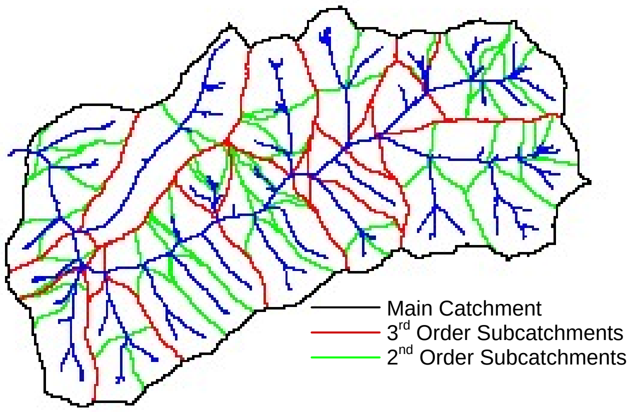

Figure 9: Automated Catchment Break-up Using Horton Stream Orders

These methods of automated catchment break-up reduce the uncertainty associated with identification of subcatchment outlets and also vastly increase the speed of catchment break-up. This increase in model setup time provides the potential for a sensitivity analysis of a hydrologic model to number of subcatchments and basis for catchment break-up, an important step which is rarely undertaken in flood and drainage investigations.

7. TOPOGRAPHIC PARAMETERISATION AND GEO-SPATIAL STATISTICS

An important aspect when using lumped hydrologic models is the assignment of lag times and associated parameters to the subcatchments. These are related to the subcatchment topographic attributes and are determined in the models from equations derived from observed hydrographs and measured subcatchment attributes. Thus both the development of lag relations using observed hydrographs, and the application of these relations to allocate lag times within the model, require extensive measurement and geo-statistical analysis of the subcatchment attributes.

Algorithms have been included with CatchmentSIM to accommodate calculation of these parameters and will automatically calculate parameters including average vectored slope, Horton drainage density, bifurcation and many others. A range of graphs can also be produced including overland / in-stream flow distance frequency distributions, bifurcation plots, hypsometric curves and others.

8. COUPLING WITH 3RD PARTY HYDROLOGIC MODELS

CatchmentSIM integrates directly with a wide range of Australian and international hydrologic models. Figure 10 illustrates the software's ability to integrate with some of the most prominent Australian hydrologic modelling packages for natural and urban catchments. Supported international models include HEC-HMS and ArcGIS. CatchmentSIM tightly couples with these 3rd party models by automatically creating run-files or import files that can be directly opened with the coupling software.

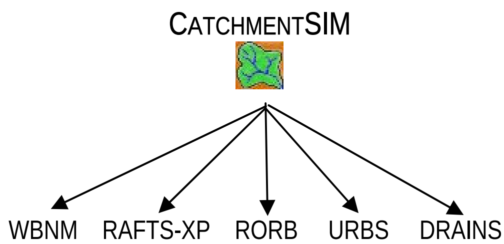

Figure 10: Supported Australian Hydrologic Models

The ease of integration of CatchmentSIM with a range of hydrologic modelling packages that are recommended for a particular region enables a sensitivity analysis to be easily undertaken using multiple hydrologic models with an identical subcatchment arrangement and associated topographic parameters. This is also an important type of sensitivity analysis rarely undertaken in flood and drainage studies.

9. CONCLUSIONS

The increasing availability of accurate GIS data-sets within Australia and around the world has opened the door to automation of many of the tasks associated with preparing hydrologic and hydraulic models. However, the algorithms included in many commercial GIS software packages to undertake these tasks are overly simplistic and are too generic to be applied with confidence in complex hydrologic and hydraulic problems.

This paper has described a suite of algorithms that are embodied with the CatchmentSIM software, and their capability to aid engineers and scientists with development of hydrologic models.

CatchmentSIM has shown considerable potential in both natural and urban catchments. The ability of the software to automatically interpolate DEMs, delineate catchments, subcatchments and predicated stream networks and tightly integrate with a comprehensive range of 'industry standard' hydrologically modelling packages should enable faster and less subjective setup of the topographic components of hydrologic models. The bonus is that this will allow users to focus their efforts on other phases of the work where expert human input is irreplaceable.

10. FUTURE RESEARCH

CatchmentSIM is currently being applied in natural and semi-urban projects in Australia and around the world. Scope exists for further work in highly urban environments, particularly in the further development of CatchmentSIM's modelling of pipe and pit networks.

Development of CatchmentSIM is set to continue and the focus of the research will remain on building a robust industry tool rather than a purely research orientated application. The goals will remain: automation, reproducibility and accuracy enhancement of currently accepted techniques for hydrologic and hydraulic modelling.

11. SOFTWARE AVAILABILITY

CatchmentSIM and tutorials can be freely downloaded from the project web-site (http://www.catchmentsim.com). Users can also freely register as a site member in order to be notified of updates.

12. REFERENCES

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APPENDIX D

CATCHMENTSIM MEMBERSHIP DATABASE

CatchmentSIM MEMBERSHIP DATABASE

This appendix presents the CatchmentSIM user membership database that has been developed over the course of the project. The information shown in the following table is a subset of the information entered by users when they sign-up in order to download the software. Several fields including username, password, email address and mailing address have been omitted from this appendix to maintain privacy commitments. Duplicate entries and obviously false sign-ups have been removed; however, in the interests of preserving the original information entered by users, no further alterations have been made to the data.

SURNAME	FIRST NAME	EMPLOYER	POSITION	REFERRAL TYPE	REFERRAL SOURCE	COUNTRY
a	mehrdad			Conference		Iran
Abu Hasan	Zorkeflee	Dept of Irrigation and Drainage, Malaysia	River Engineer	Search Engine	msn	Malaysia
Achmad	Mahmud	USQ	Research Student	Conference	Hydrologic Simposium (Melbourne)	Australia
adugna	tamene	addis ababa university	graduate student	Search Engine		Ethiopia
Aifesehi	Pedro	university of sci. & tech Port harcourt	Ph.d student	Link	bossintl.com	Nigeria
akbari	abolfazl		student	Search Engine		Iran
Alahmadi	Fahad			WBNM Link	Link From WBNM	Australia
Alberto	Benavides	University of Costa Rica		Link	Google.co.cr	Costa Rica
Alias	Shahrizal			Search Engine	yahoo	Malaysia
Altonen	Brian	Clarke Environmental	Field Engineer	Search Engine	Yahoo, entered 'Hydrology GIS Free Downloads'	United States
Anderson	Brett	University of Melbourne	Postgrad Student	Search Engine	google	Australia
andrieu	herve	LCPC - division Eau	researcher	Link		France
Anke	Fabian	Self-employed	Geologist	Search Engine	Google	South Africa
Arbuckle	Chris	Otago Regional Council	Manger Resource Science	Other	refer to site by coleague	New Zealand
Arulmani	Parasuraman	Ashokleyland Ltd	Sr. Civil Engineer	Search Engine	www.google.com	India

SURNAME	FIRST NAME	EMPLOYER	POSITION	REFERRAL TYPE	REFERRAL SOURCE	COUNTRY
Arunakumaren	Jerome			Search Engine		Australia
atri	reza			Search Engine		Iran
Awadallah	Ayman		Assistant Proefessor Cairo University	WBNM Link	Link From WBNM	Egypt
B	T	Cambridge University	Student	Search Engine	Google	United Kingdom
bachu	Radha Krishna Murthy	rmsi	project lead	Search Engine	Google	India
Bacigalupo	Dominic	UNSW	student	Search Engine		Australia
Bailloeul	Timothee	student	remote sensing	Search Engine	google	China
bajelan	ayat	ahvaz_chamran university(gondi shapor)	ms student of civil eng.	Conference	rainfall-runoff prediction using artificial neural network	Iran
Bakir	Mohammad	hohai university	master student	Search Engine	www.google.com	China
Ball	James			WBNM Link	Link From WBNM	Australia
Bandara	palitha	hardy Advanced Technical Institute	Lecturer	Search Engine		Sri Lanka
Bandini	Valeria			Search Engine	Google	Australia
Bardsley	Mike	City Design	Civil Engineer	Search Engine	google	Australia
barnard	yolanda		engineer	Search Engine	messanger	New Zealand
Baron	Bruce	Gold Coast City Council	Design Coordinator	Other		Australia
Bartho	Nick	Kellogg Brown & Root Pty Ltd	Civil / Water Engineer	WBNM Link	Link From WBNM	Australia
Batchu	Madhavi Latha			Search Engine	Google	Australia

SURNAME	FIRST NAME	EMPLOYER	POSITION	REFERRAL TYPE	REFERRAL SOURCE	COUNTRY
Bateman	William			Conference		United Kingdom
Battad	Dionisio	Forests Service	Nat. Resources Analyst	Search Engine	netscape	Australia
Bedford	Dave			Search Engine		Australia
Bedi	Anmol			Other		Australia
Benavides	Jude	Rice University	Ph.D. Candidate / Research Project Manager	Other	Reference from co-worker	United States
Berton	Frank	Maunsell	Senior Engineer	Search Engine	Google	Australia
Bhat	G.K			Search Engine	Google	Australia
bhatti	tariq	university of the Punjab Lahore Pakistan	Lecturer	Search Engine	yahoo	Pakistan
Bills	Bruce			Search Engine		Australia
bilotta	vincent			Search Engine	google	United States
Birnie	Tim	Earth Tech Engineering	Design Engineer (Environmental)	Conference	Civil Engineers Australia June 2003	Australia
Bishop	Warwick	Water Technology	Senior Engineer	Search Engine	anzwers	Australia
Bodhinayake	Dayananda			Other		Australia
Boemelburg	Johann			Search Engine	Google	Germany
Bolaji	Gbolagade	University of Agriculture, Abeokuta. NIGERIA	Lecturer	Search Engine	Goggle	Nigeria
Bool	Arthur	QUT	Student	Other	Uni lecturer	Australia

SURNAME	FIRST NAME	EMPLOYER	POSITION	REFERRAL TYPE	REFERRAL SOURCE	COUNTRY
Borges	Luciane	Catholic University of Pelotas	Professor	Other		Brazil
Bosch	G			Search Engine	google	Australia
bouanan	aissa	CID	Ing.	Link	BossIntl	Morocco
Bozorg-Zadeh	Mostafa	Independent Consulting Engineer	Independent Consulting Engineer	Conference	David Maidment's Handbook of Hydrology,1993	Iran
Brander	Kent	Emmons & Olivier Resources, Inc.	Water Resources Engineer	Search Engine	Yahoo!	United States
Brar	Navjit			Search Engine	google	United States
Brough	Andrew			Search Engine	Google	Australia
Brun	Tony	City of Bunbury	Executive Manager City Development	Conference	Engineers Australia (Civil Edition)	Australia
Burkard	Dietmar			Search Engine	www.google.de	Germany
Calabretta	Gianluca			Search Engine		Australia
Campagne	Lorraine			Search Engine	google	Australia
Cardenas	Maria	BOKU		Search Engine	Delined Subcatchment	Austria
Caridei	Francesco			Search Engine		Italy
ch	Ted			Search Engine		Australia
chang	harry	national taiwan normal u.	associate professor	Search Engine		Taiwan
Charlton	Berk	Meridian GeoSystems	Consultant	Search Engine	Google	United States
chaudhuri	sujoy	ecollage	researcher	Search Engine	google	India
ChaussΘe	Denis	ISIM	student	Conference	from a friend	France

SURNAME	FIRST NAME	EMPLOYER	POSITION	REFERRAL TYPE	REFERRAL SOURCE	COUNTRY
Cheeseman	Peter	H2OK Systems	Engineer Technician	Link	Boss International, HEC-RAS forum	United Kingdom
chen	kefan			Search Engine		Australia
Chen	Chester			Search Engine		Australia
Cheng	PS			Other	HEC-Ras forum	Australia
Cheung	Leonard	Griffith University	PhD Scholar	Search Engine	Yahoo	Australia
Childs	John	RPI Hartford		Search Engine	google	United States
chong	ken	University of Adelaide	student	Search Engine	www.yahoo.com	Australia
Choy	Warren	DBA	Environmental Consultant	Search Engine	Google	Australia
Christensen	Robert			Search Engine		Australia
Chui	Peter	Hong Kong	Engineer	Other		Hong Kong S.A.R.
Ciesiolka	Cyril	Dept of Natural Resources	scientist	Other	previous training course	Australia
Clark	Ian			WBNM Link	Link From WBNM	Australia
Coello	Xavier	ESCUELA POLITECNICA NACIONAL	CIVIL ENGINEER	Search Engine	google	Ecuador
Collings	Greg	Lawson & Treloar Pty Ltd	Engineer	Search Engine	Google	Australia
Comerford	Laurie	CADApps	Applcation Engineer	Other		Australia
corney	trevor	Ullman & Nolan Consulting Pty Ltd	Design Office Manager	Conference	Institute of Enginers	Australia
cortina	fernando			Search Engine		Australia
Costin	Steven	Structel Pty Ltd	Design Engineer	Other	Engineers Australia Magazine	Australia

SURNAME	FIRST NAME	EMPLOYER	POSITION	REFERRAL TYPE	REFERRAL SOURCE	COUNTRY
cottam	dean	Berrigan Shire Council	Design Engineer	Search Engine	yahoo	Australia
Cottee	Vern	Cottee's Enterprises Pty Ltd	Chief Engineer and Managing Director (retired)	Search Engine		Australia
Cox	Graeme	Hydro Tasmania	Engineer Hydrologist	Conference	IEAUST Hydrology Wollongong 2003 Proceedings	Australia
Cruz	Daniela	SMSB		Search Engine	Google	Portugal
Daniel	Pierre	ingenior		Search Engine	google	France
Dassanayake	Kithsiri	Dept. of Land and Water Conservation		Search Engine	msn search	Australia
Davies	Simon	Golder Associates	GIS Manager	Search Engine	Google WBNM	Australia
Davies	Philip	CSIRO Land and Water	Spatial Analyst	Link	http://www-civil.eng.monash.edu.au/research/groups/water/RORB	Australia
de lucia	franco			Search Engine		Australia
Della	Michael	Cardno MBK	Senior Environmental Engineer	WBNM Link	Link From WBNM	Australia
demarco	alessandro	archeology	archeology	Search Engine		Italy
Demetriou	Charles			Conference	IEAust	Australia
demirkiran	oguz	khgm	engineer	Search Engine		Turkey
Densten	Anthony	Water Solutions Pty LTd	Water Engineer	WBNM Link	Link From WBNM	Australia
desai	darshan			Search Engine	google	Australia

SURNAME	FIRST NAME	EMPLOYER	POSITION	REFERRAL TYPE	REFERRAL SOURCE	COUNTRY
dewu	yang			Search Engine		China
diab	mohammad	sydney		Other		Australia
dias	samuel	for	msc	Search Engine	yahoo	Brazil
Dip	Roberto Jesus			Other		Argentina
Dodson	Roy	Dodson & Associates, Inc.	President	Search Engine	yahoo	United States
Doerflinger	Gerald		Watershed Management Engineer	Search Engine	google	Cyprus
Doley	Todd	SAIC		Search Engine	Google	United States
Dong	Haibin			Search Engine	excite	Australia
Doskocil	Jiri	Jicarilla Apache Nation	GIS System Manager	Search Engine	msn	United States
Dou	Khan			Search Engine	google	United States
Dragicevich	Vic	SMEC	Senior Civil Engineer	Search Engine		Australia
dressel	urs	siegen	civilengeneering	Search Engine	google	Germany
Dunn	Scott			Search Engine	Google	Australia
East	Jeff	U.S. Geological Survey	Hydrologist	Search Engine	Google	United States
Edwards	Richard	Microsoft	Programmer/ Writer	Search Engine	Google	United States
Ehlert	Volker	Centre for Agricultural Landscape and Land Use Research (ZALF)		WBNM Link	Link From WBNM	Germany

SURNAME	FIRST NAME	EMPLOYER	POSITION	REFERRAL TYPE	REFERRAL SOURCE	COUNTRY
Elbadawy	Omar	Cairo Univ	Hydrologist	Search Engine	ESRI	Egypt
Ellis	Robin	QLD Dept. of Natural Resources and Mines	Natural Resource Info Officer	Search Engine	Google	Australia
Ellis	Daniel	PGAL	Civil Engineer	Link		United States
Ellison	Robert	MH Palmer Consulting Engineers	Project Engineer	WBNM Link	Link From WBNM	Australia
El-Naqa	Ali	Hashemite University	University Professor	Link		Jordan
Elphick	Matt	Jones Nicholson P/L	Design Engineer	Other	through university study	Australia
Emmanuel	Kabantchenko			Search Engine	google	France
Erofeev	Ilya			Link	vterrain.org	Australia
Erturk	Ali	ITU	University	Other	By mail group	Turkey
Esposito	Paolo		engeneer	Search Engine	google	Italy
Estifanos	Medhin	SFA		Other	Instructor	United States
Everett	Jason	University of NSW	PhD Student	Conference	Smiths Lake Estuary Process Study	Australia
Ezzy	Graham	Bureau of Meteorology	Hydrological Services Manager	Other		Australia
fabio	di nasso	geologist	geologist	Search Engine	google	Italy
Farabi	Houshang	The Australian National University	Student	Search Engine		Australia
farina	joseph			Search Engine		Australia

SURNAME	FIRST NAME	EMPLOYER	POSITION	REFERRAL TYPE	REFERRAL SOURCE	COUNTRY
faust	brad	PHD		Search Engine		Australia
favreau	gerald	CommunautΘ urbaine		Search Engine	for RORB software	France
feng	jennifer			Search Engine		Australia
feng	Xiaobo			Search Engine		Australia
Fernandes	Nuno		Environmental Eng.	Search Engine		Portugal
Ferraz	Silvio			Search Engine	google	Australia
ferreira	marcos		projetista	Other	internet	Brazil
Flaxman	Michael	Harvard Graduate School of Design	Postdoctoral Fellow	Search Engine		United States
Fleeting	Jamie	John Amey & Associates	Consultant	Search Engine	google	Australia
Flores	Edson	Engineer	Engineer	Search Engine	yahoo	Bolivia
Fontana	Nicola		Engineer	WBNM Link	Link From WBNM	Italy
Foumelis	Michael			Search Engine	google	Australia
Froehlich	Otavio			Search Engine	google	Brazil
gabdiaz	Gabriel Daz Padilla	INIFAP	Mc	Search Engine	google	Mexico
Galgale	Harshal	Student	Student	Search Engine	Google	India
Ganstrom	Stephen	Tri-Core Engineering LLC	Project Engr.	Search Engine	Google	United States
Gear	Allan			Search Engine		Australia

SURNAME	FIRST NAME	EMPLOYER	POSITION	REFERRAL TYPE	REFERRAL SOURCE	COUNTRY
george	matthew	university	students	Search Engine	looking for a RORB download	Australia
Ghasempour	Farnush	TU-Dresden	Ph.D. Student	Search Engine	Google.com	Germany
Gibbons	Steve	City of Stow	GIS Coordinator	Search Engine	Google	United States
Gillespie	Doug	ETS Group	Civil Design Drafter	Link	wbnm site	Australia
Gipea	gipea			Search Engine		France
Girgin	Serkan	Middle East Technical University Department of Environmental Engineering	Res. Asst.	Other		Turkey
glamore	william	Wollongong Uni	PhD Candidate	WBNM Link	Link From WBNM	Australia
Goleby	Alice	UOW	Student	Search Engine	Google	Australia
Gomez	Juan	Mexican Institute of water Technology	Enginner	Search Engine		Mexico
Gorman	steven			Other	GCCC	Australia
Gorman	Lachlan			Search Engine		Australia
Goyen	Allan	XP Software	Director	Other		Australia
Greenhow	Tim	freelance	Planning consultant	Other		Sweden
Grisotto	Silvio		Dr	Search Engine		Italy
grundy	christine	GHD	Environmental Engineer	Search Engine		Australia
Guang	Liu	Peking University, Beijing, China	Ph.D. candidate	Search Engine	www.google.com	China

SURNAME	FIRST NAME	EMPLOYER	POSITION	REFERRAL TYPE	REFERRAL SOURCE	COUNTRY
Guerin	Phillip	Uni	Student	Other		Australia
Guo	Liwen	Wollongong university		Search Engine		Australia
Gupta	Mukesh	kharagpur,india	student(M.Tech.)	Other		India
Gupta	Apurba	National Environmental Engineering Research Institute (NEERI)	Water Resource Management Research	Search Engine	Google	Iraq
GÚrald	Favreau			Search Engine	www.google.fr	France
Gurung	Shivaraj	DPIWE	Hydrologis	Search Engine		Australia
Guthrie	Mick	Queensland University of Technology Australia	Student	Search Engine	www.anzwers.com.au	Australia
Gyford	David			Search Engine		Australia
Hai	Mwangi	International Center for Research in Agroforestry	Graduate student	Search Engine	Google	Kenya
Haines	Mike	SAEPA		Search Engine	Google	Australia
hala	robin		student CTU	Search Engine		Czech Republic
Hale	James	Home Use		Other	colleague	United Kingdom
Halloul	Haitham	60	System Depart Mgr	Search Engine	google.com	Kuwait
Hammouri	Nezar	Hashemite University	Assistant Prof.	Search Engine	www.google.com	Jordan
Han	Henry			Search Engine	asd	Australia

SURNAME	FIRST NAME	EMPLOYER	POSITION	REFERRAL TYPE	REFERRAL SOURCE	COUNTRY
haque	sanaul	Systems Research Institute	Project Internship	Search Engine	www.google.com	India
Harte	Michael	Central Queensland University	Lecturer - GIS	Other	from a friend who is an engineer	Australia
Hay	Gavin	GHD	Water Resources Engineer	Search Engine	google	Australia
hbh	Matthew			Search Engine		Australia
Heller	Werner	Buero Heller	Dipl.-Ing.	Other	tip of a friend	Austria
Henson	Tadd			Search Engine		United States
Heryansyah	Arien	Utsunomiya	Student	Search Engine	google	Japan
hewitt	Ricky	Ganza Consulting Services	Project Engineer	Other	friend	Australia
hicham	hajji			Search Engine	google	Australia
Higginbotham	Bret	Nathan D. Maier Consulting Engineers Inc.	Senior Designer	Other	e-mail link	United States
Higham	Martin			Other		Australia
Hoekenga	Jonathan	Emmons and Olivier Resources	GIS Technician	Other	co-worker	United States
Hogan	Michael		Design Engineer	Search Engine	yahoo	Australia
Hooper	John			Search Engine		Australia
horne	damien			Link	the virtual terrain project website	Australia
Horton	Peter			Other		Australia
Hoxhaj	Fatos	Institute of Hydrology	Head of department	Link	HEC-RAS Group	Albania

SURNAME	FIRST NAME	EMPLOYER	POSITION	REFERRAL TYPE	REFERRAL SOURCE	COUNTRY
Hoxhaj	Fatos	Inst. of Hydrometeorology	Dr	Link	NASA	Albania
Hsu	Chiang-An			Search Engine	Google	Taiwan
Htun	ThetTin	Mt. Popa Area	Assistant Lecturer	Search Engine	google	Myanmar
huang	ming-jer			Other	vtp	Australia
Humer	G³nter	Consulting engineer DI Humer	senior consultant	Other	HEC newsgroup	Austria
hunukumbura	Priyantha	University of Peradeniya	student	Search Engine	google	Sri Lanka
Ibrakhimov	Hayot			Other	Friend gave it to me	Australia
Ibrakhimov	hayot	Germany	Junior researcher	Other	my friend gave the link to this web-site to me	Uzbekistan
Ichim	Sebi			Link	vterrain.org	Romania
Iftikharuddin	Faruk	UWS	Research Assistant	Other	From a hydrologist friend	Australia
Ignacio	Toro	PUC	Inginerφa	Search Engine	RORB	Chile
Imanuddin	Martinez			Search Engine		Australia
Inouye	Paul	M & E Pacific, Inc.	Project Engineer	Link	Boss International forum	United States
Isabirye	Moses	National Agric. Research Organization	Research Scientist	Other		Uganda
J	C	Brisbane City Council	GIS Programmer	Other		Australia

SURNAME	FIRST NAME	EMPLOYER	POSITION	REFERRAL TYPE	REFERRAL SOURCE	COUNTRY
jalali	Ramin	iran	consulter	Conference		Iran
James	Corey			Search Engine	awfulvista	Australia
Jenkins	Doug	Interactive Design Services	Owner	Conference	Engineers Australia	Australia
Jensen	Joy	MZM Inc.	Engineering Analyst	Search Engine	www.google.com	United States
jha	atmanand			Search Engine		Australia
Jol	Lonard	INRA	researcher	Search Engine	Google	France
Jonat	Frank	EADS - Dornier GmbH	System Planner Geoinformation	Search Engine	google	Germany
Jones	Alex	North Shore Paving	civil Engineer	Other		Australia
Jordan	Trent	MIM	Environmental Engineer	WBNM Link	Link From WBNM	Australia
Jordan	David	Trinity College Dublin	Phd student	Search Engine	Google	Ireland
jorge	salazar			Search Engine		Bolivia
Joseph	Jean Vitalien	FAU	Engineering	Search Engine	FAU	United States
Juan	Juan Melendez	Self	Civil Engineer P.E.	Other	Hec-Ras User Group (BOSS)	United States
Juergen	Vogt	Joint Research Centre	Research Scientist	Other		Italy
Jung	Young Hun			Search Engine		Australia
Jung Min	Lee	engineer	student	Search Engine		Korea
K	NS	KYTC	Engineer in Training	Search Engine	google	United States

SURNAME	FIRST NAME	EMPLOYER	POSITION	REFERRAL TYPE	REFERRAL SOURCE	COUNTRY
Kang	Poh Jing	University of Adelaide		Link	through web site of WBNM	Australia
Kater	Jesse	UoW	Student	WBNM Link	Link From WBNM	Australia
Katzil	Yaron	Technion	Student	Search Engine	google	Israel
kaulgud	shrinivas	Texas Tech University	Reserch Assistant	Search Engine	HEC HMS	United States
Keats	Andrew			Search Engine		Australia
khamassi	faouzi			Search Engine		Australia
khiadani	mehdi			Search Engine		Australia
Khider	Abel	Corticomp	Research	Search Engine		Tanzania
khosroshahi	mohamad		Researcher	Search Engine		Iran
Kim	Kyung-Tak	Korea Institute of Construction Technology	Engineer	Search Engine	www.google.co.kr	Korea
klaus	michael	Private Citizen	City Resdent Whose Neighborhood Floods	Link	http://vterrain.org/	United States
Klingseisen	Bernhard	Curtin Uni of Technology(Perth,WA) / Carinthia Tech Institute (Villach, Austria)	Student	Search Engine	google: keywords: dem flow lines	Austria
Koo	Man-Kit	City of Toronto	Modelling Engineer	Search Engine	Yahoo	Canada
Korn	Steven			Other	GCCC	Australia
Krammer	Christian	Amt der Niederoesterreichischen Landesregierung, Abt. Hydrologie		Other	personal information by a friend	Austria

SURNAME	FIRST NAME	EMPLOYER	POSITION	REFERRAL TYPE	REFERRAL SOURCE	COUNTRY
ks	sandip	rajasthan,india	research fellow	Search Engine	google.com	India
Kuhnke	Bill	Alberta Environment	Team Leader	Link	hecras-ug@bossintl.com	Canada
Kulkarni	Nagaraj	National Informatics centre	Principal Systems Analayst	Other		India
kuzu	mer	Hydrogeology	Engineer	Search Engine	good	Turkey
Kwasniewski	Jacek	Cobb Fendley & Associates	Project Manager	Search Engine	Google	United States
Lafazanis	Costas	Trikala - Greece	Civil and Environmental Engineer	Search Engine	lycos	Greece
Langston	James	Engineer		Search Engine	Google	Australia
Lawry	Elise	Water Technology	Project Engineer	Other	program when it expired	Australia
Lazaro	Roger	Hassal & Associates, International	Monitoring and Evaluation Specialist	Search Engine	www.google.com	Philippines
LE	Peter	UTS	Stormwater Engineer	Conference	uts	Australia
Le	Khoa	Student		Search Engine		Australia
Le Phuoc	Thanh			Conference	Free GIS	Australia
Lee	Caster	National Cheng-Kung University	Associate Researcher	Search Engine	Yahoo	Taiwan
Lee	Allan	Forestry Tasmania	Engineer Civil Projects	Conference	Civil Engineers Australia June 2003	Australia
lehung	lehung	manager	Eng	Search Engine	internet	Vietnam
Leinster	Shaun	belleng Pty Ltd	Senior Water Resources Engineer	WBNM Link	Link From WBNM	Australia

SURNAME	FIRST NAME	EMPLOYER	POSITION	REFERRAL TYPE	REFERRAL SOURCE	COUNTRY
Leonard	Campbell	CLA Consultants	Director	Search Engine		Australia
Leris	Evangelos	Consultant		Search Engine	Google	Greece
Lev	George	Freelance	Geophysicist	Other		Canada
Li	Xiaobo			Search Engine		Australia
Li	Hengpeng			Search Engine		China
Li	Carl	CH2M	Engineering	Search Engine	Yahoo	Hong Kong S.A.R.
Lilja	Harri	Viasys Oy		Search Engine		Finland
Lim	Richelieu Felipe	Department of Public Works and Highways		Search Engine		Philippines
Lin	Yu Hsuan			Search Engine		Australia
Lindsay	John			Search Engine	Google	Australia
Lishman	James	Database Systems	CEO	Search Engine	yahoo - Flow Routing	South Africa
liu	pengju	academy of forestry.ac.cn		Search Engine	google	China
Lofberg	Milton			Search Engine	Google	Australia
Loh	christy			Search Engine		Australia
Loos	Sibren	UvA	Student	Search Engine	google	Netherlands, The
Lopez Pairet	Raul	Irrigare Consultores	INGENIERO CIVIL	Search Engine	google	Uruguay
Loxton	Toby	GHD PTY LTD	Senior Hydrologist	WBNM Link	Link From WBNM	Australia
Lugovoy	Victor			Other		Australia
Luker	Greg	Southern Cross University	GIS Lab Manager	Search Engine	google	Australia

SURNAME	FIRST NAME	EMPLOYER	POSITION	REFERRAL TYPE	REFERRAL SOURCE	COUNTRY
M	Tariq		Engineer	Search Engine		Australia
Mahiny	Rassoul	ANU	Ph.D. Student	Other		Australia
majtan	stefan			Search Engine	google	Australia
Malone	Terry	Bureau of Meteorology	Senior Engineer	Other		Australia
Man	Bat	PBP	IT Man	Search Engine	google	Australia
Manca	M.Grazia	National Council of Research	Senior Researcher	Search Engine	google	Italy
Marcus	Warren	EPA	GIS officer	Search Engine	google	Australia
Markowski	Jacek	Agricultural University of Wroclaw	Ph.D.	Search Engine	google	Poland
Marshall	Brian	KBR/QUT	Civil Designer/Bachelor of CE student	Other	Used software at QUT	Australia
Marthick	John			Search Engine	Search for Michael Boyd on UOW site	Australia
Martin	Chris	Wilkinson Developments	Site Manager	Search Engine	Australian Rainfall and Runoff	Australia
Martinez	Javier	Universidad de la Frontera		Link	free-gis list	Chile
Matthews	Stephen	Robert Bird & Partners	Senior Civil Project Manager	WBNM Link	Link From WBNM	Australia
McCowen	Douglas			Search Engine	Google	United Kingdom

SURNAME	FIRST NAME	EMPLOYER	POSITION	REFERRAL TYPE	REFERRAL SOURCE	COUNTRY
McLuckie	Duncan	Department of Sustainable Natural Resources	Flood Specialist	Search Engine	google	Australia
McPherson	Bronson	Manly Hydraulics Laboratory	Flood Engineer	WBNM Link	Link From WBNM	Australia
mcwaters	john			Search Engine		Australia
Mehmood	Khalid	Dillon Consulting	Hydraulic Specialist	Search Engine	google	Canada
Meier	Jens			Search Engine		Germany
Mendoza	Diomar	Empresa Nacional de Energia Electrica	Head of Water Resources Dpt.	Other		Honduras
Meynink	Bill	PSM Australia Pty Ltd	Principal Hydrologist	Search Engine		Australia
Millar	Ben	GHD Pty Ltd	Environmental Engineer	WBNM Link	Link From WBNM	Australia
Min	Yaowu	CWRC	Flood forecasting	Other	Terry Malone	China
Mirza	Lt Col Naseer	Bahria Town	Consultant Engineering	Search Engine	yahoo	Pakistan
Misund	Arve	Interconsult	Hydrogeologist	Other		Norway
Moh	Assaba			Search Engine		Australia
mokhtari	ahmad			Search Engine	google	Iran
Molina	Jose Luis	Student	mR	Search Engine		Mexico
Molnar	Daniella	York Univeristy	Graduate student	Other		Canada
Montgomerie	Peter	Calare Civil Pty Ltd	Design Draftsman	Other		Australia
moret	emilio			Search Engine		Australia

SURNAME	FIRST NAME	EMPLOYER	POSITION	REFERRAL TYPE	REFERRAL SOURCE	COUNTRY
Morgan	Marcus	University of Wollongong		WBNM Link	Link From WBNM	Australia
Morgan	John	CTE Engineers	Sr. Hyd. Eng.	Other	e-mail on BOSS HEC-RAS list	United States
Morris	Ken	City Design - Brisbane City Council	Principal Engineer Water & Environment	WBNM Link	Link From WBNM	Australia
moshenberg	kari			Search Engine		Australia
Moss	David	CivilTech P/L	Director	Conference	Engineers Australia	Australia
Mrs.	Jennifer	Texas Tech University	Student Assistant	Search Engine	msn.com	United States
mullany	wal			WBNM Link	Link From WBNM	Australia
Muller	Robert	UTS	Masters Student	Other		Australia
Murawski	Paul	US Army Corps of Engineers	Hydraulic Engineer	Other	user forum	United States
Murdoch	Jason	BradLees Consulting	Associate	Other		Australia
Murray	Peter	Brisbane City Council - City Design	Surveyor - systems	Search Engine	google	Australia
Mwanjalolo	Majaliwa	Student		Search Engine		Congo, Democractic Republic of the
Nader	Farzad	Tamavan Consulting co.	Hydrologist	Search Engine	Google	Iran
nadery	hadi	informal	watershit	Search Engine		Iran
Nanadoum	Kinagoto	WR Engineering	Student	Search Engine	Google: GIS Hydrology	United States

SURNAME	FIRST NAME	EMPLOYER	POSITION	REFERRAL TYPE	REFERRAL SOURCE	COUNTRY
Napoli	Rosario	Istituto Sudio e Difesa Suolo	researcher	Search Engine	google	Italy
nassirifard	mohammad	ministry of agriculture	engineer	Link	iranhydrology	Iran
nawras	nawras			Search Engine	google	Australia
Ney	Syd	Sydney	Engineer	Search Engine	Yahoo	Australia
Nichet	sebastien	Newcastle University (UK)	Hydrology	Search Engine	Google	United Kingdom
Nicholls	Scott			Search Engine	google	Australia
nouri	hamid	malayer	teacher of university	Search Engine		Japan
oberdorf	brian	Ardill Payne and Partners	Engineer	Link	WBNM site	Australia
Ogilvie	Harry	University of Edinburgh		Search Engine	google	United Kingdom
Olaya	Victor			Link	FreeGis.org	Australia
O'Loughlin	Geoffrey	Anstad Pty Ltd		Other		Australia
O'Reilly	Damien	RMIT	Student	Search Engine		Australia
othman	khalil	hohai university	ph,d student	Search Engine	google	China
Pacheco	Ricardo			Search Engine	Google	Portugal
Pallares	Alejandro			Search Engine	google	Australia
Pan	Ben			Search Engine		Australia
parasuraman	sureshbabu			Search Engine	google	Australia
parekh	hardik	lamar university, texas	environmental engg	Search Engine	google	United States

SURNAME	FIRST NAME	EMPLOYER	POSITION	REFERRAL TYPE	REFERRAL SOURCE	COUNTRY
Park	Minkyu	Yooshin	Water Resources Engineer, Dam Design	Other	BOSS homepage, Q&A board	Korea
Passchier	Ron	Delft Hydraulics	Hydrologist	Search Engine	Google	Netherlands, The
Patel	Gaurangkumar	University of Western Sydney	Master Degree Student	Search Engine	Google	Australia
Patel	Priyank			Search Engine	google.com	India
Paterdis	Stephen	Queensloand University of Technology	Student	Search Engine		Australia
Paun	Gabriel	gisWizard	Geographic Information Officer	Search Engine	google	United States
Pearcey	Mark	Water & Rivers Commission	A/Senior Engineer	Other		Australia
Pearson	Drew	City of Gastonia	Zoning Administrator	Search Engine	typed Hec HMS	United States
peloton	pelle	asf	asf	Search Engine	g	Australia
Pent	Ed			Search Engine		United States
Perez	Uriel	Universidad del Tolima	Profesor	Search Engine	search in internet	Colombia
Phillips	Doug	University of Calgary	Computational Science Consultant	Search Engine	Google	Canada
Pillai	Gopakumar	CWRDM, Kerala, India (Student, Kyoto University)	Scientist	Search Engine		India
Piva	Alberto			Search Engine		Australia
plogmeier	christoph			Search Engine	google/hec hms	Australia

SURNAME	FIRST NAME	EMPLOYER	POSITION	REFERRAL TYPE	REFERRAL SOURCE	COUNTRY
Polo	Paolo	MED Ingegneria	Engineer	Other	HEC-RAS forum	Italy
Pott	Andrew	CPH Water	Hydrologist	WBNM Link	Link From WBNM	South Africa
potter	matthew			Search Engine		Australia
Pozzi	Will	Global Carrying Capacity	System Administrator	Link	terrain modeling	United States
Pradhan	Dinesh	Darjeeling , West Bengal , India	Landslide at Darjeeling Areas	Conference	From The Telegraph Newspaper Knowhow 18th August 2003	India
prasetyo	suwandi	TECHNICIAN	GIS SPECIALIST	Search Engine		Indonesia
preis	ami	Technion,Israel Institute of Technology	graduate student	Conference		Israel
Prenzler	Jason	Griffith University	Student	Search Engine	Google	Australia
Priante	Mauro		engineer	Search Engine	yahoo.it	Italy
Price	Curtis	US Geological Survey	Physical Scientist/GIS	Conference	Hydroinformatics 2002 conference in Wales	United States
qavami	kamran			Other	a colleague	Iran
radmanesh	feridon	university	student	Search Engine	MSN	Iran
raftram	rafa	student	student	Other	hec-ras user group	Iran
raleigh	sara		Environmental Officer	Search Engine	yahoo	Australia

SURNAME	FIRST NAME	EMPLOYER	POSITION	REFERRAL TYPE	REFERRAL SOURCE	COUNTRY
Ramanamaharishi	Sakthivel	DEPARTMENT OF GEOLOGY, BHARATHIDASAN UNIVERSITY	RESEARCH SCHOLAR	Search Engine	google	India
rao	rup			Search Engine		Australia
Rashid	Harun			Search Engine		Australia
ravazzani	giovanni			Link	www.freegis.org	Australia
Ray	Paul	Texas A&M, College Station, Tx	Student	Search Engine	google	United States
ray	amit			Search Engine	www.google.com	India
reddy	vinil	MWH Global	Staff Engineer	Search Engine		United States
Rehman	Habib			Search Engine		Australia
Rey	Brian			Search Engine		United States
Rezayan	Hani			Search Engine		Australia
Ricks	Milton	Federal Govt.	Civil engineer	Search Engine	msn	United States
Roberts	Amanda	Griffith University	Environmental Engineering	Search Engine		Australia
Roberts	Mark	NDMCE	Project Manager	Conference	HEC-RAS users group at BOSS International	United States
Robertson	Gillies	Tafe NSW Sydney Institute	Bush Regenerator	Search Engine		Australia
rondon	miguel			WBNM Link	Link From WBNM	Australia

SURNAME	FIRST NAME	EMPLOYER	POSITION	REFERRAL TYPE	REFERRAL SOURCE	COUNTRY
roos	magda	Council for Geoscience	GIS Technician	Search Engine	Excellent	South Africa
rossi	lele			Search Engine		Australia
Rostedt	Bengt	hobbyist	CFO	Search Engine	Googlr	Finland
Rubiano	Jorge			Search Engine		Australia
Rubiano	Jorge			Search Engine		Australia
Rubio	Maricel	TokyoTech	Research student	Search Engine		Japan
s	saravanan			Conference	TransCat	India
saavedra	Carlos	student	research	WBNM Link	Link From WBNM	Netherlands, The
Saavedra	John J.	S&B Infrastructure, Ltd.	Chief Hydraulic Engineer	Conference	TSARP Conference	United States
sahu	bhupesh	orissa	cad engg	Search Engine	google search	India
Saikasem	Solarwish	Naresuan University	Prof.	Search Engine	google	Thailand
Sakulsonbunsiri	Pinpetch	Chiang Mai University	graduate student	Search Engine		Thailand
sam	Kim			Search Engine		Malawi
sang cheol	lee			Search Engine		Australia
Sargent	David	Sargent Consulting	Principal	Link	Monash Uni RORB site	Australia
sarkar	ashis	Presidency College	Professor	Other		India
Saunders	Ann	Mott MacDonald Group	Environmental Engineer	Search Engine	google	United Kingdom

SURNAME	FIRST NAME	EMPLOYER	POSITION	REFERRAL TYPE	REFERRAL SOURCE	COUNTRY
Savoie	Francois			Search Engine	Yahoo!	Canada
Say Cheong	New	SSI Consulting Engineers	Civil Engineer	Search Engine	yahoo	Malaysia
Schalk	Ken	Tonkin Consulting	Director	Conference		Australia
Schymitzek	Irene			Other		Australia
Seaton	Hamish	self employed		Search Engine	google search: interpolation dem	New Zealand
sekovanic	leonard			Search Engine	google	Croatia (Hrvatska)
Semerdjiev	Rouslan	Manager of Hydropoer division, Energoproekt Jsc	engineer	Search Engine	good	Bulgaria
sepehri	sina			Search Engine		Turkey
Sharma	Ashok	CSIRO		Search Engine		Australia
Sharp	Chris			Search Engine	anzwers	Australia
Sheehan	Brian	Gold Coast City Council	2/3 Level Support Officer	Other		Australia
Shrestha	Madhusudan	Gifu University	Reseach fellow	Search Engine	google	Japan
Simms	Ava	University of Wollongong	PhD Student	Other		Australia
Simpson	Robert	Coffey Geosciences Pty Ltd	Engineer	Search Engine		Australia
Singh	Achut	Hatch Associates	Senior Water Engineer	WBNM Link	Link From WBNM	Australia
Smith	Dan	ERDC	Ecologist	Link		United States

SURNAME	FIRST NAME	EMPLOYER	POSITION	REFERRAL TYPE	REFERRAL SOURCE	COUNTRY
song	kechao	cold and arid regions environmental and engineering institute of CAS	research assistant	Search Engine	hydrotope by google	China
Spry	Robert	Cardno Willing Pty Ltd	Principal	Other		Australia
Stephens	David	Bureau of Meteorlogy	Hydrology Engineer	Other		Australia
Stephens	David	Bureau of Meteorology	Engineer	Other	Previous use	Australia
stewart	joel			Search Engine		Australia
Stojnic	Vladimir	SCA	Modelling planning engineer	Search Engine		Australia
Stokes	Bernie	Commonwealth Bureau of Meteorology	GIS Integration Project Manager	Other		Australia
Subra	Vijay	completed a course at Sydney Institute of Technology	Civil engineer	Search Engine		Australia
Sumairi	Razif			Search Engine	google	Australia
Sung	Leliel			Link	www.vterrain.org	Taiwan
Suriney	Jason			Search Engine		Australia
Sustic	Diana			Search Engine		Australia
Swan	Rob	Lawson & Treloar		Search Engine	google	Australia
Syme	Bill	WBM Pty Ltd	Associate	WBNM Link	Link From WBNM	Australia
Szulc	Deborah	QUT	Student	Link		Australia
t	thomas	self	engineer	Search Engine	google	India

SURNAME	FIRST NAME	EMPLOYER	POSITION	REFERRAL TYPE	REFERRAL SOURCE	COUNTRY
tajarudin	husnul azan			Search Engine		Australia
Tamene	Lulseged	Mekelle University, Ethiopia	Currrently, PhD Student	Search Engine	Google engine on keywords "catchment shape calculation"	Germany
Tanner	Henry	student		Search Engine		Australia
Taylor	Ian			Search Engine		Australia
Taylor	Bruce	Edmiston & Taylor	Director	Conference	EA Journal	Australia
Teegavarapu	Ramesh	University of Kentukcy	Professor	Search Engine	google	United States
Teng	Mee-Lok	Barwon Water	Water Resources Engineer	Conference	IEAust	Australia
terneak	josef			Other	BOSS INTL NEWS	Australia
Tetley	David	Patterson Britton & partners	Project Engineer	Other		Australia
Tewnion	Angus	Carter & Burgess	Water Resources Engineer	Other	Co-worker	United States
thakur	praveen			Search Engine		India
Thapa	Phatta	IoE Pulchowk Campus	NA	Search Engine	search engines	Nepal
Thibeault	Denis	Public Works Department	Urban/Transportation Planner	Search Engine	GOOGLE	Cayman Islands
Thomson	Lachlan			Search Engine	Answers	Australia
Thomson	Rhys	Lawson and Treloar		Search Engine		Australia
Thomson	James	Brisbane City Council	Data Analyst	Other		Australia

SURNAME	FIRST NAME	EMPLOYER	POSITION	REFERRAL TYPE	REFERRAL SOURCE	COUNTRY
Tirado	Francisco Mario	Universidad Nacional de Jujuy	Agric.Eng.	Search Engine	Google	Argentina
Touchette	Eric			Search Engine		Canada
Tovizi	Andras	VITUKI Rt.	technical assistant	Other	colleague told me	Hungary
Tremblay	Charles			Search Engine	dogpile	Canada
Trezise	Frank			Search Engine		Australia
trihono	kadri	Watershed Post Graduate	Lecture	Conference		Indonesia
trihono	kadri	Trisakti University/ Bogor Institut of Agriculture	Decision Support System for Catchment Management	Search Engine	google search	Indonesia
tubby	chris			Search Engine	google	United Kingdom
tuckers	brent			Search Engine		Australia
Tulachan	Ravi	Shoalhaven City Council	Floodplain Engineer	Link	www.uow.edu.au	Australia
Tunnicliffe	Jon	University of British Columbia	Phd - Researcher	Search Engine	Google	Canada
Tunnicliffe	Nick	Maunsell West Australia	Transport Engineer	Conference	Engineers Australia	Australia
Tuyen	Tran Huu			Search Engine		Australia
Tylcer	Ondrej			Other	colleague	Australia
Uduwalage	Subash	Serandib Engineers Pty ltd	Senior Civil Engineer	Conference	Institution of Engineers Magazine	Australia

SURNAME	FIRST NAME	EMPLOYER	POSITION	REFERRAL TYPE	REFERRAL SOURCE	COUNTRY
Unucka	Jan	University Of Ostrava	Hyrology	Other	from Technical University of Ostrava, 708 00	Czech Republic
uyenkhoi	nguyenam 60			Search Engine		Vietnam
V	Ben	Engineer		Other		France
VanDrie	Rudy	BALANCE RND	Engineer	Other		Australia
Vassilakis	Emmanuel	University of Athens	PhD Student	Other	Collegue student	Greece
Venteris	Erik	USDA-ARS-EQL	Post Doc	Search Engine	google	United States
vertzonis	marika			Conference		Australia
vijay	subra			Search Engine		Australia
Vinh	Quang Vinh			Search Engine		Australia
Odarski	Wojtek	Adam Mickiewicz University	geologist	Search Engine		Poland
wahbi	joe	australia	desiner	Search Engine	internet	Australia
Wang	Zhishan	Zhengzhou Institute of Technology	associate professor in mechanical engineering	Search Engine		China
Weissling	Blake			Search Engine		United States
Wenk	Gerald			Search Engine		Australia
Whishaw	Nathan			Search Engine	anzwers	Australia
Wijesiri	Subasing	GCCC	Strormwater Engineer	Search Engine	Google	Australia
Williams	Blair			Search Engine	yahoo	Australia
Williams	Cassandra	University of Melbourne	Student	Search Engine	google	Australia

SURNAME	FIRST NAME	EMPLOYER	POSITION	REFERRAL TYPE	REFERRAL SOURCE	COUNTRY
Williams	Steve			Other	BOSS Intl HEC Listserv	Australia
Wilson	Wade			Search Engine		Australia
Win	Zaw	Dept. of Commerce, Dams & Civil	Design Engineer	Conference	Engineers Australia	Australia
Womersley	Tim	Water Technology	Project Engineer	Other	colleague	Australia
Wong	Wilson	unemployed		Search Engine	Yahoo	Malaysia
wu	Yongsheng	tsinghua University	Dr.	Search Engine	google	China
xiaobo	fengxiaobo			Search Engine		Australia
Yang	Joe		Research Association	Search Engine		Canada
Yates	Derek	National Centre for Groundwater Management, UTS	Principal Scientist	WBNM Link	Link From WBNM	Australia
Yoseph	Binyam	Technical University of Dresden	Research Staff	WBNM Link	Link From WBNM	Germany
Yung-Chang	Chuang	National Taiwan University	research assistant	Search Engine		Taiwan
zan	guo	bnu		Search Engine	http://www.google.com	China
Zhan	X.			Search Engine		Australia
Zhang	Shangyou			Search Engine		Australia
zhu	honglei			Search Engine		Australia
zizo	hazim		gis & rs Specialist	Link	from google site	Egypt